



Presented for 29th International Symposium on Ballistics

Some Features and Applications of Ballistic Science and Technology in China

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Edinburgh, Scotland

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- ▼ Interior Ballistics
- ▼ Intermediate Ballistics
- ▼ Exterior Ballistics
- ▼ Terminal Ballistics
- ▼ Future Development



Introduction

■ Chief scientist of China Academy of Ordnance. Professor of Nanjing University of Science and Technology. Director of the National Key Laboratory of Transient Physics.

Main research interests are on hypervelocity launching, hypervelocity flight, and hypervelocity impact.



Prof. Baoming Li



Prof. Hongzhi Li

■ Academician of China Engineering Academy. Former President and Professor of Nanjing University of Science and Technology.

For long time, engaged in the research and teaching on defense science and technology.



Introduction



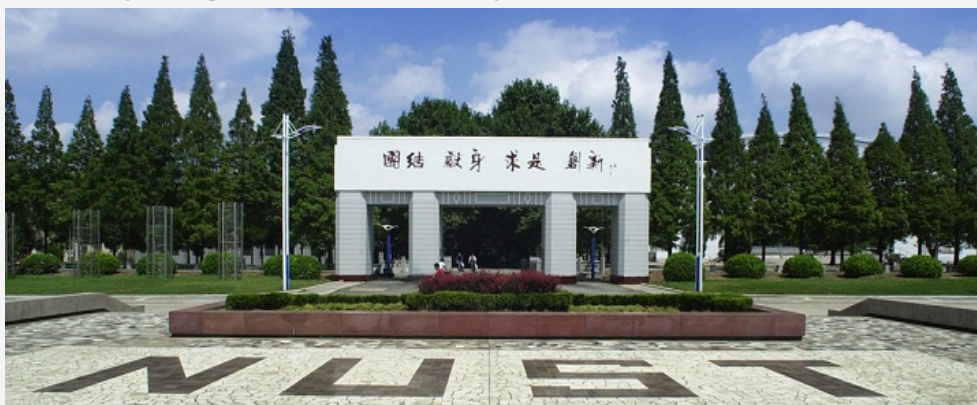
China North Industries Group Corporation (NORINCO)



- Anti-terrorism mission
- Effective damage
- Precision strike
- Air defense and anti-missile
- Long-range suppression
- Armored assault



Nanjing University of Science and Technology (NUST)



Mission: NUST aims at developing itself into a major base in China for training high quality and creative personnel, high-tech research and transfer and academic and cultural exchanges as well as an indispensable force for China's economic and social progress and national defense modernization.

Value: Unity, Dedication, Truth, Innovation.



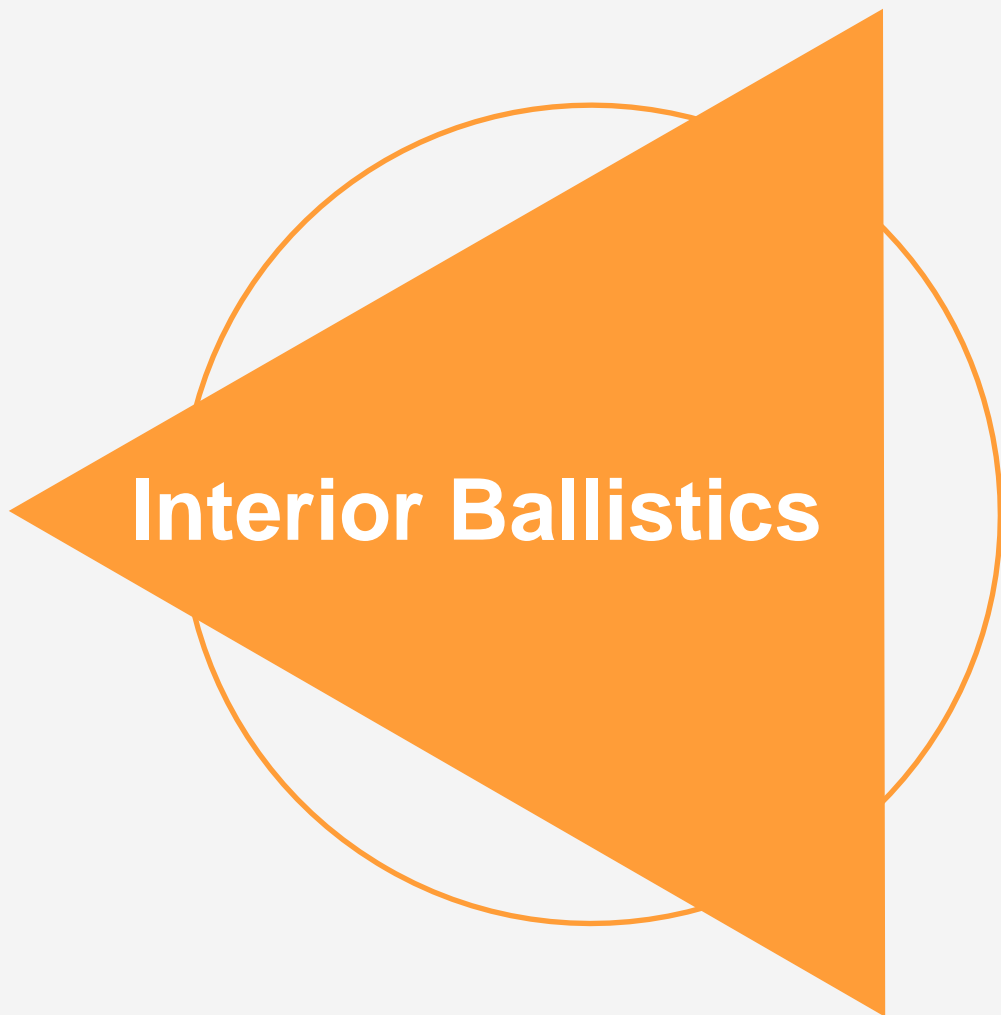
Introduction

China attaches great importance to innovate developments in defense technology. Since the beginning of twenty-first century, the science and technology of China Ballistics has been developing rapidly and significant progresses have been made in the fields of interior ballistics, intermediate ballistics, exterior ballistics and terminal ballistics. A lot of breakthrough has been achieved in theory, mechanism and focused technology.





CONTENT



Electrothermal-Chemical Launch



Electromagnetic Launch



- Plasma Ignition Mechanism
- Non-Fourier Law Thermal Response
- Transient Burning Rate Model
- Interior Ballistic Optimization Design
- Interior Ballistic Potential Equilibrium Model
- Multi-Dimensional Multi-Phase Flow Simulation
- High Precision Measurement
- Launching tests

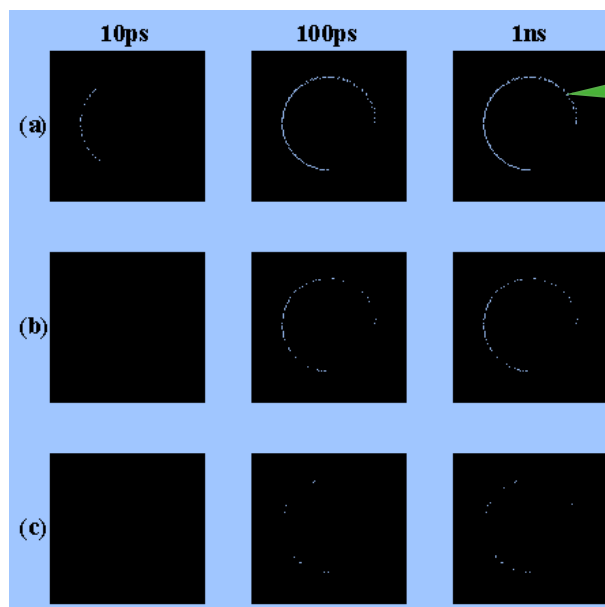
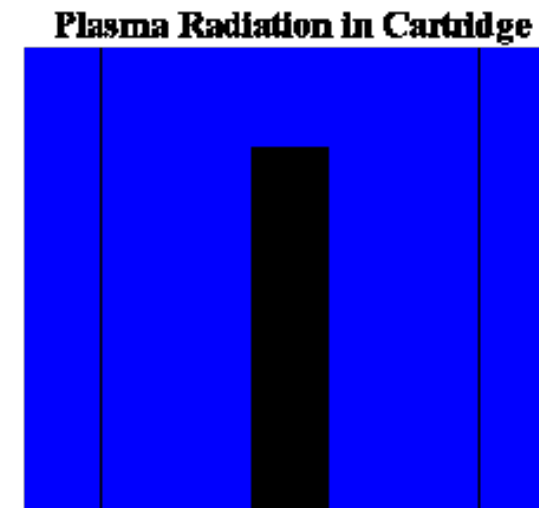
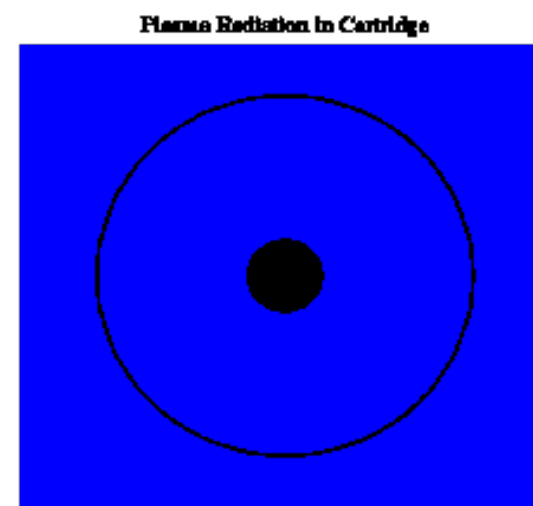
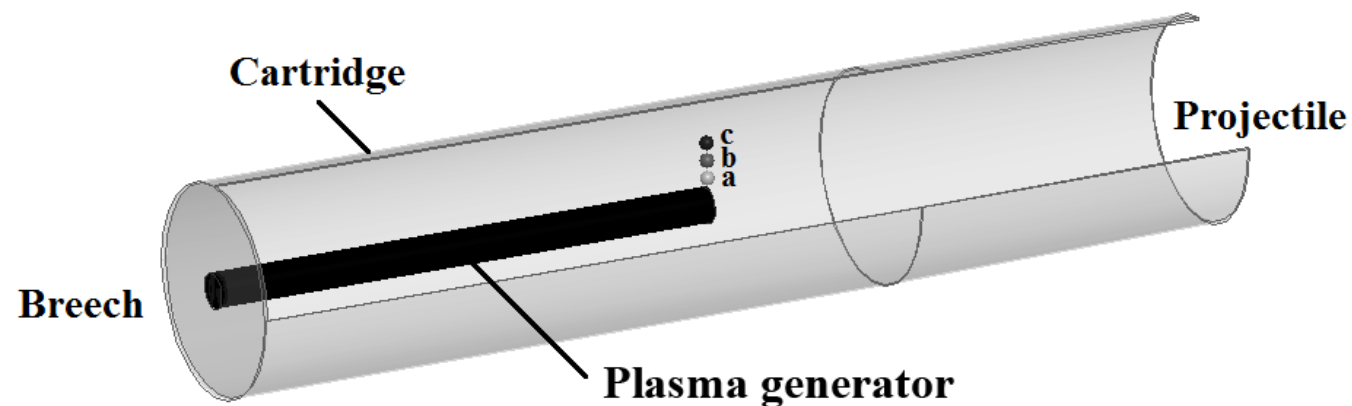




Interior Ballistics

Plasma Ignition Mechanism

Electrothermal-Chemical Launch



Energy Skin Effect

Based on the MCM, a numerical model is established to simulate the plasma radiation process and discuss the mechanism of plasma ignition in ETC launchers. Because of the high power plasma and limited space characteristics of transient radiation, local solid propellant grains' surface can quickly achieve ignition point by the early transient plasma radiation.



Interior Ballistics

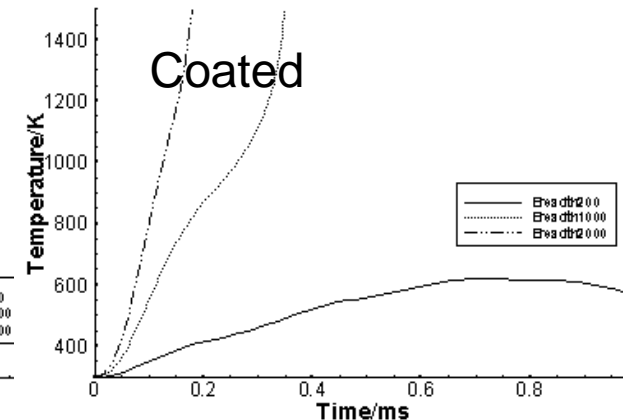
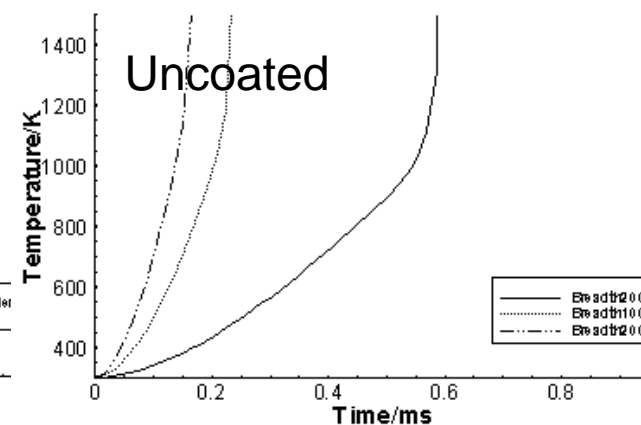
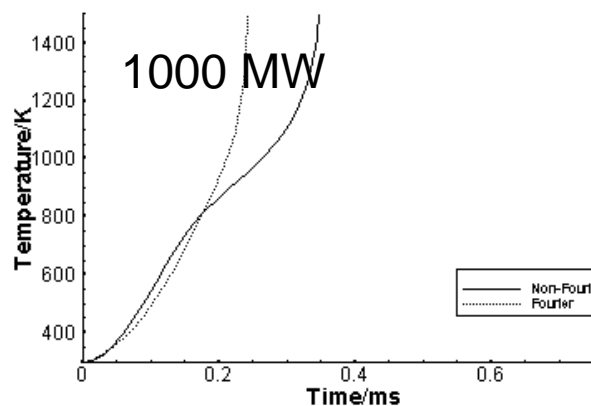
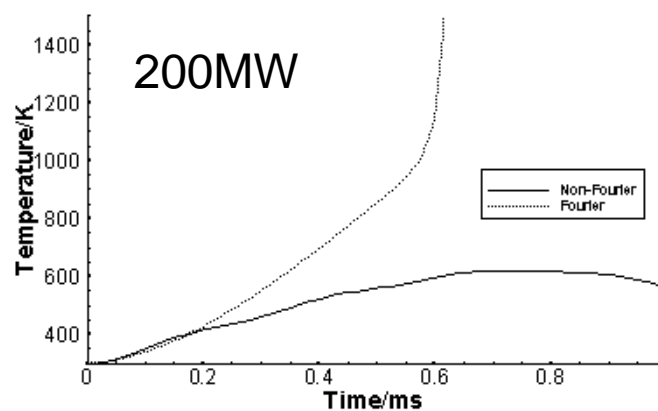
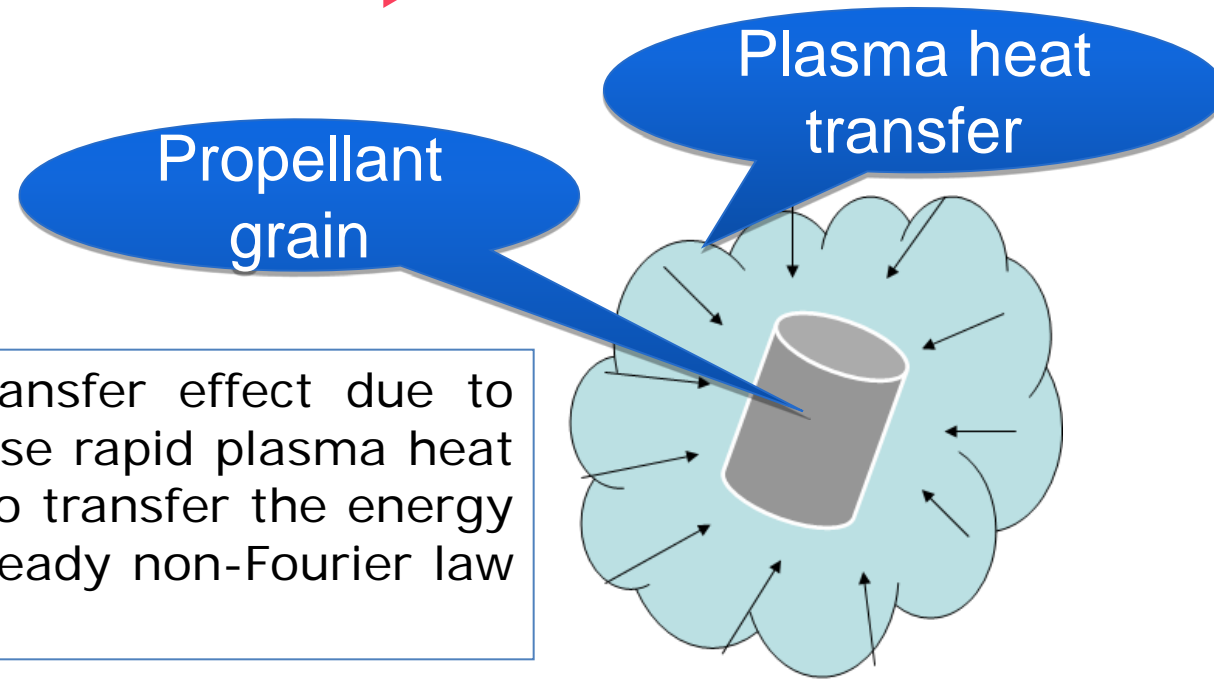
Electrothermal-Chemical Launch

Non-Fourier Law Thermal Response

$$\tau_0 \frac{\partial^2 T}{\partial \tau^2} + \frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial r^2} + \frac{2a}{r} \frac{\partial T}{\partial r} + \frac{ZQ}{\rho c} \exp\left(-\frac{E}{RT}\right)$$

$$\tau_0 \frac{\partial^2 T}{\partial \tau^2} + \frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial r^2} + \frac{a}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} + \frac{ZQ}{\rho c} \exp\left(-\frac{E}{RT}\right)$$

Plasma ignition model of non-Fourier law heat transfer effect due to thermal boundary layer. Because of the highly intense rapid plasma heat transfer, the propellant grain has not enough time to transfer the energy from the surface to the inner. This is a kind of unsteady non-Fourier law thermal response of the propellant grain.



Decrease of ignition delay with the increase of plasma energy

Non-Fourier effect is more remarkable for coated propellant

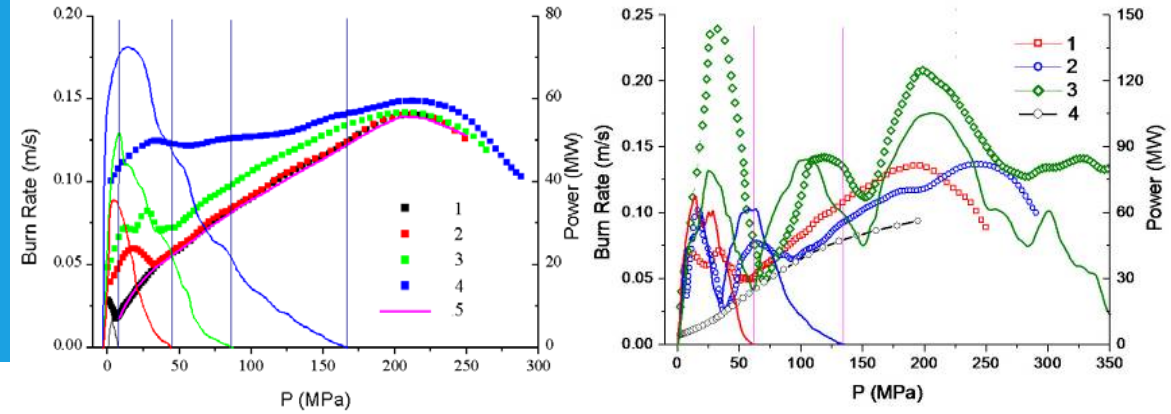


Interior Ballistics

Transient Burning Rate Model

Closed bomb tests show that the plasma can enhance the burning rate of propellant especially under the condition of low and medium pressure, and the augmented combustion rate is strongly dependent on the electric discharging power, waveform and coupling with the propellant.

Electrothermal-Chemical Launch



Woodley's Law

$$u = u_1 p^{n_1} (1 + \beta_e P_e)$$

Vieille's Law

$$u = u_1 p^{n_1}$$

Krier's Law

$$u = u_1 p^{n_1} \left(1 + \frac{\alpha(t) n_1}{u_1^2 p^{2n_1+1}} \frac{dp}{dt} \right)$$

Electric Enhance Factor

Both electric power and pressure gradient are considered

Transient Model

$$u = u_1 p^{n_1} \left(1 + \frac{\alpha(t) n_1}{u_1^2 p^{2n_1+1}} \frac{dp}{dt} \right) (1 + \beta_e P_e)$$

Pressure gradient



Interior Ballistics

Electrothermal-Chemical Launch

Interior Ballistic Optimization Design

Objectives

$$\max f(X) = [v_0(X), \eta_w(X), \eta_g(X)]^T$$

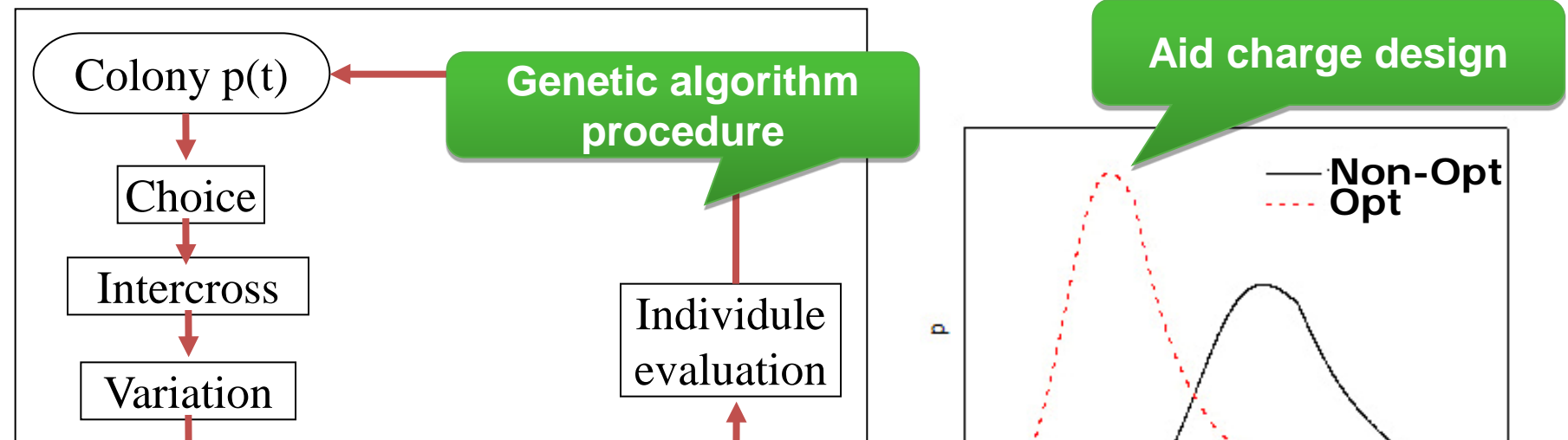
$$\min g(X) = [p_m(X), p_k(X), l_k(X)]^T$$

- ✓ Fast calculation
- ✓ Small sample
- ✓ Satisfy the local estimation

Restrictions

$$p(X) \leq P_{\max}$$

$$l_k \leq 0.75$$



An interior ballistic optimization model is established to optimize the bore structure and loading parameters when the projectile mass, muzzle velocity and maximum pressure are specified.



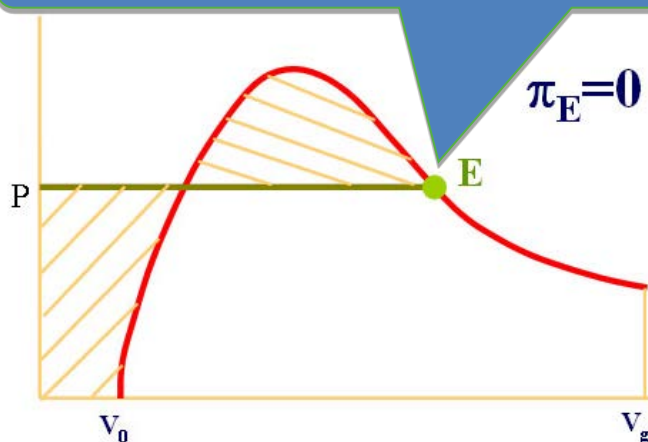
Interior Ballistics

Electrothermal-Chemical Launch

Interior Ballistic Potential Equilibrium Model

The interior ballistic potential equilibrium theory is a phenomenological analysis method to characterize the combustion enhancement effect of propellant interacting with high power electrically discharging-supported plasma. This method based on the statistic thermodynamics, introduced the total pressure impulse instead of the burned propellant web size. The potential equilibrium point can be approximate as the burning end point of interior ballistic process.

potential equilibrium point



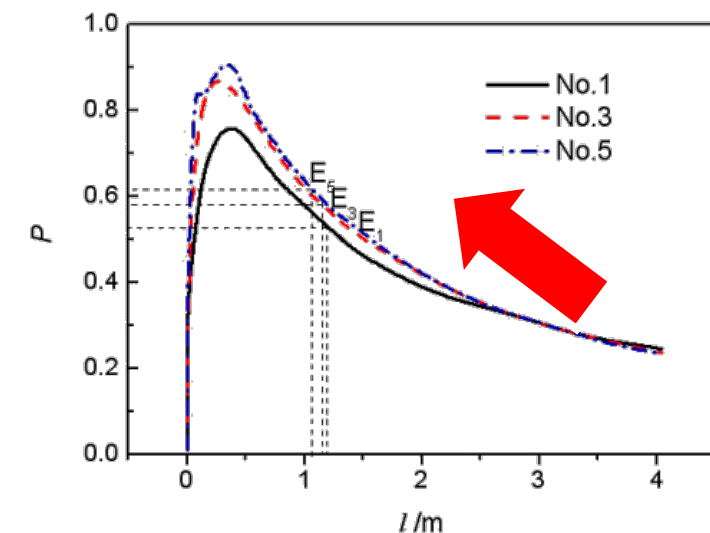
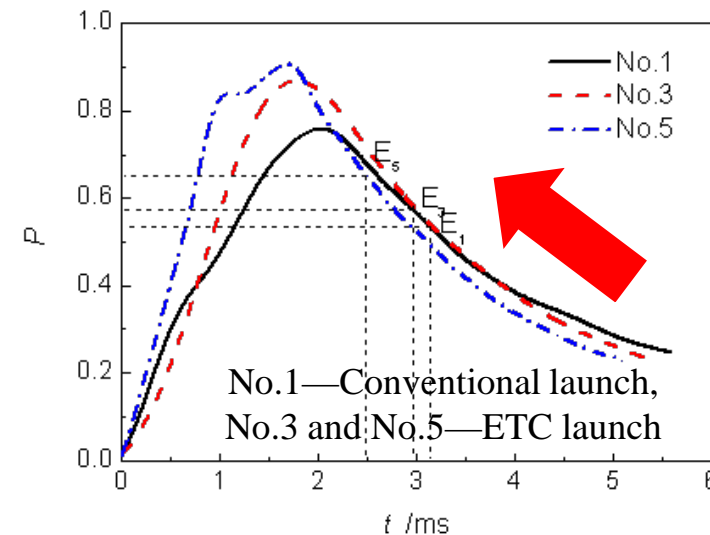
$$\pi_E = 0$$

$$\pi_\psi = f' \omega \beta' \psi$$

$$f' = f + E_{plasma} (K - 1) / \omega \psi$$

$$P \left(V + V_0 - \frac{\omega}{\rho} - \left(\alpha - \frac{1}{\rho} \right) \omega \psi \right) = f \omega \psi + (K - 1) E_{plasma} - (K - 1) \int_0^V P dV$$

Modification of impetus due to plasma injection



Potential equilibrium point shift with the increase of plasma energy

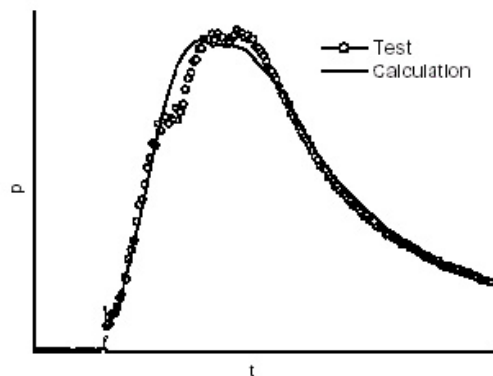


Interior Ballistics

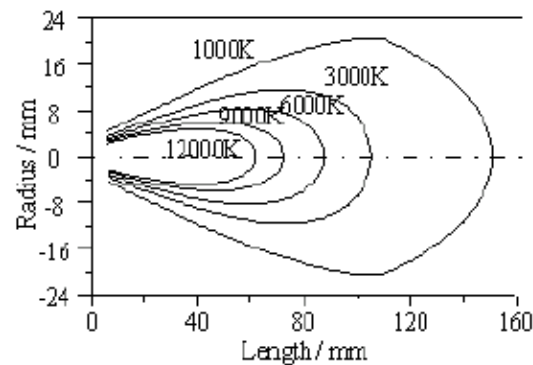
Multi-Dimensional Multi-Phase Flow Simulation

Electrothermal-Chemical Launch

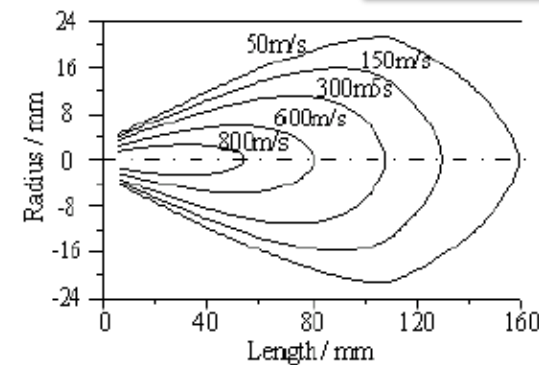
Small caliber ETC launch



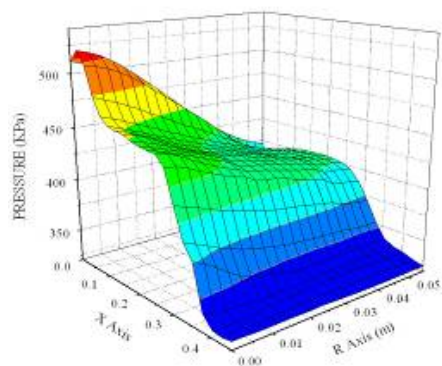
Bore pressure



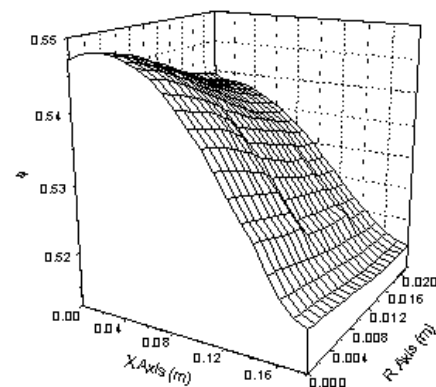
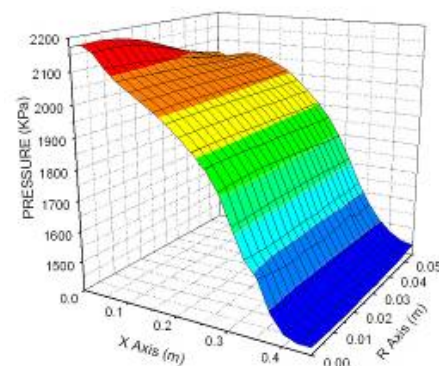
Plasma temperature



Plasma velocity



Transient pressure field



Transient porosity field

A multi-dimensional multi-phase flow dynamic model is established to simulate the ETC interior process, including the pressure, plasma temperature and velocity temporal-spatial distribution, etc.

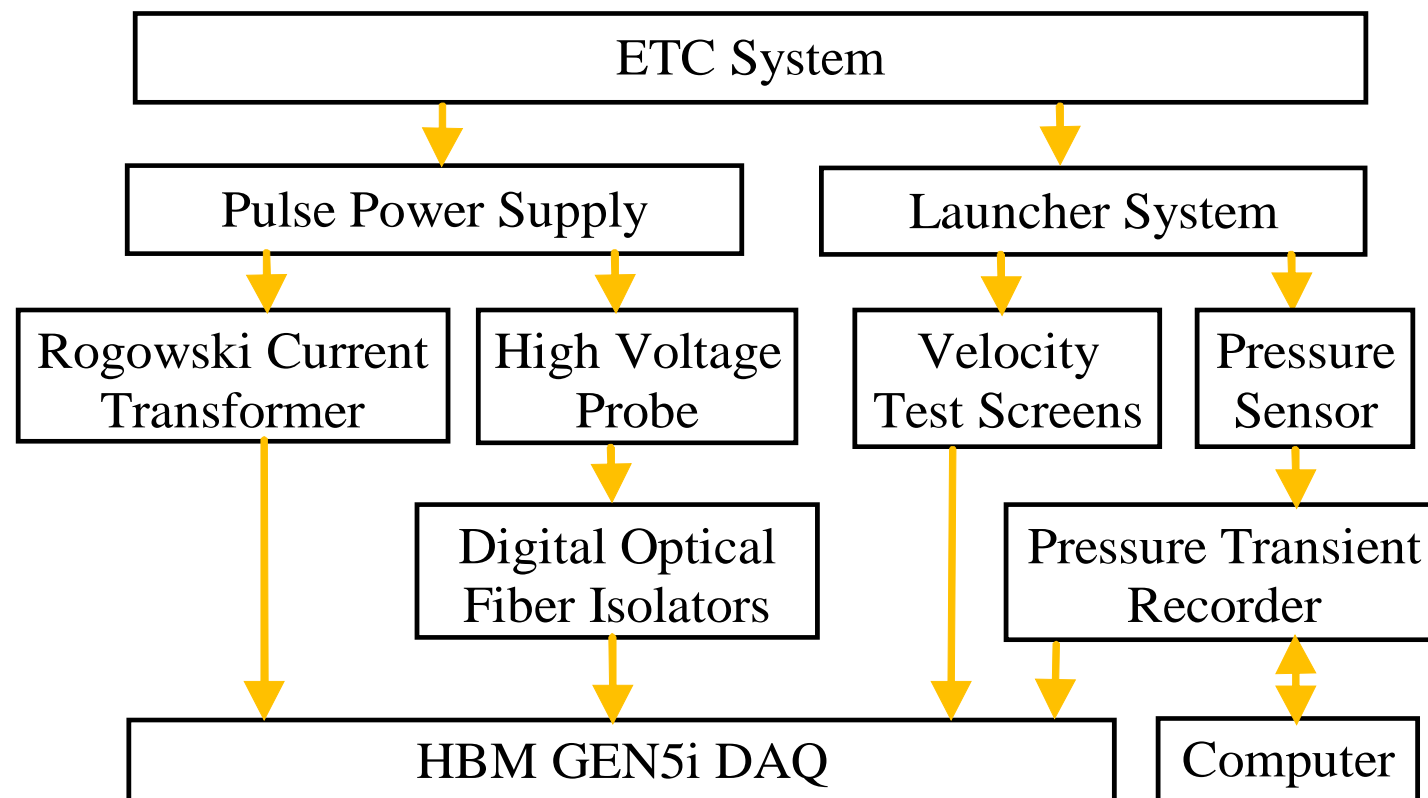


Interior Ballistics

High Precision Measurement

Electrothermal-Chemical Launch

- ✓ PULSED CURRENT
- ✓ PULSED VOLTAGE
- ✓ BARREL PRESSURE
- ✓ MUZZLE VELOCITY



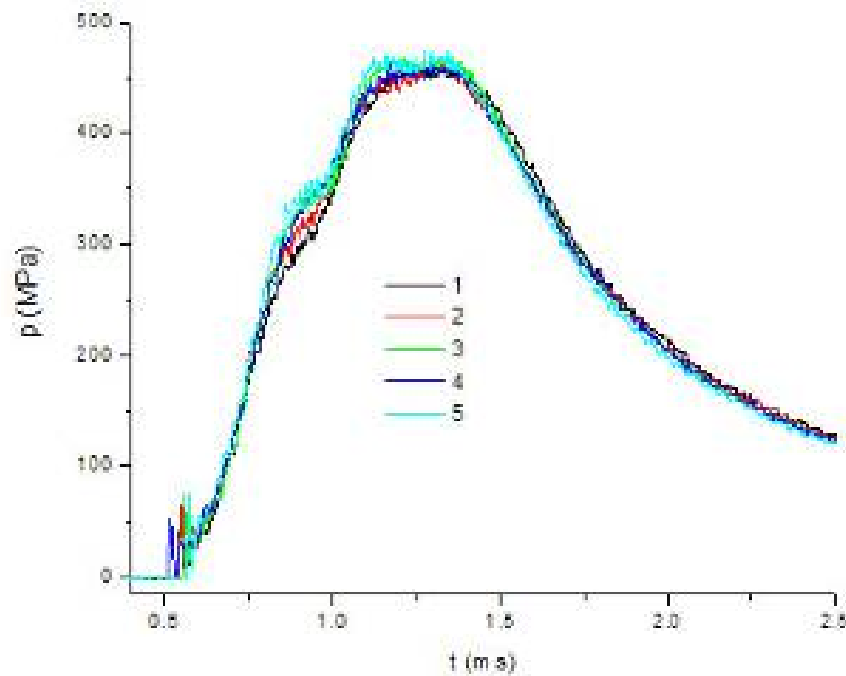


Interior Ballistics

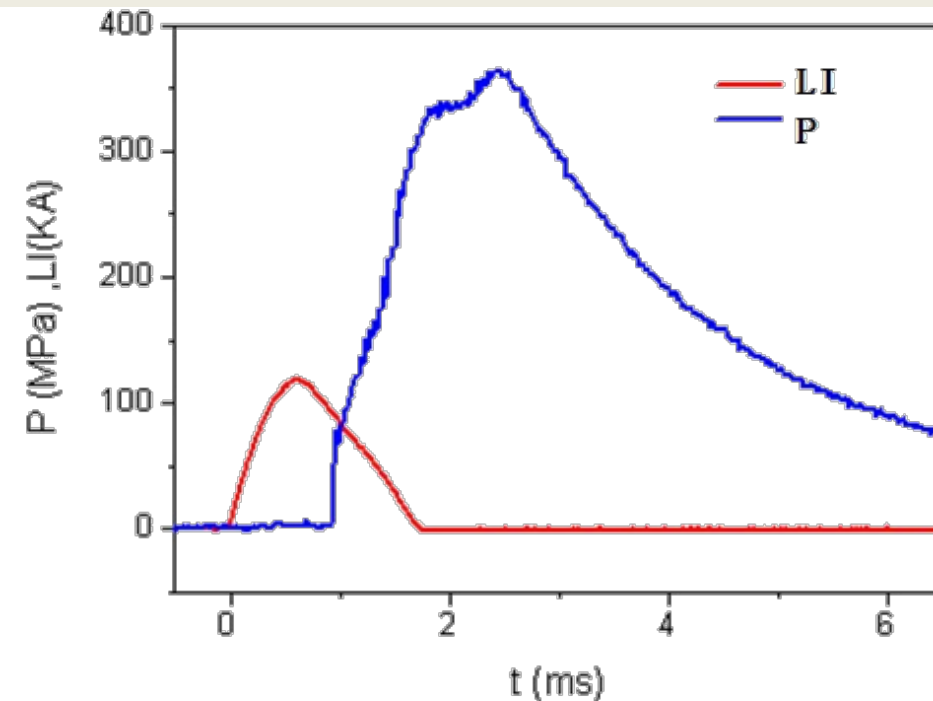
Electrothermal-Chemical Launch

Launching tests

Small and medium caliber ETC launching tests show that the bore pressure history has the high precision ignition, good consistency and platform effects in controlled fashion.



Small caliber ETC launch



Medium caliber ETC launch



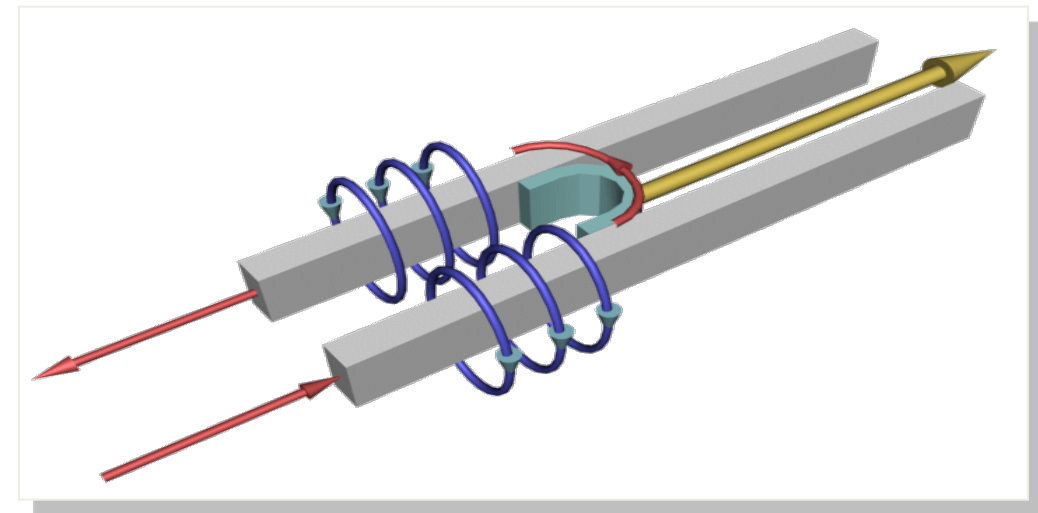
Interior Ballistics

Electromagnetic Launch

3D Transient Multi-Physical Fields Simulation

Impact Dynamics Simulation

Multi-Physical Fields Measurement

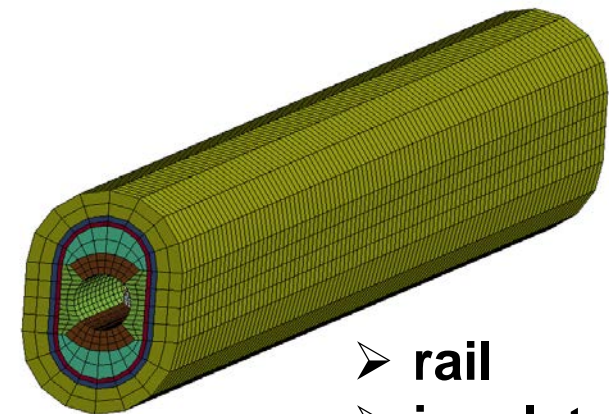




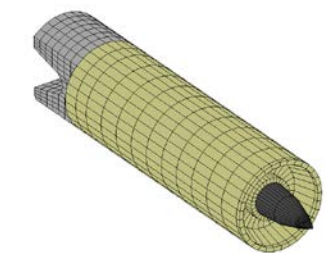
Interior Ballistics

Electromagnetic Launch

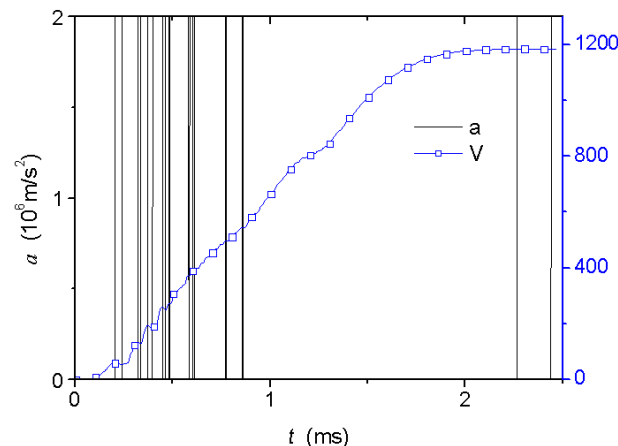
3D Transient Multi-Physical Fields Simulation



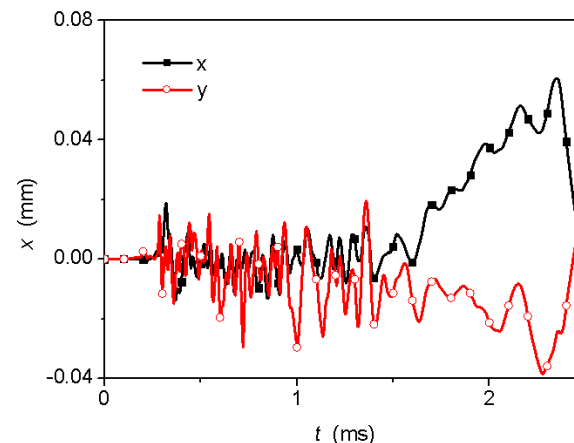
- rail
- insulator
- fiber wind



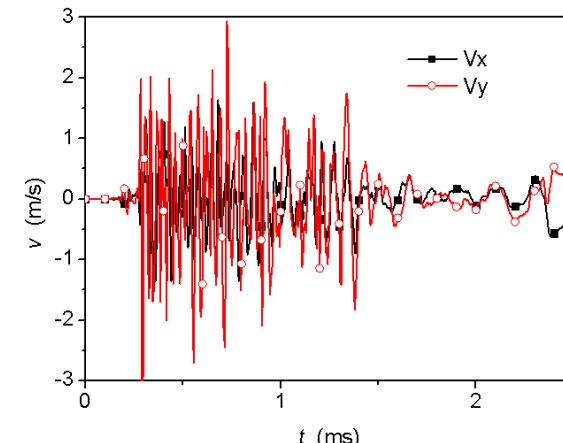
- projectile
- armature
- sabot



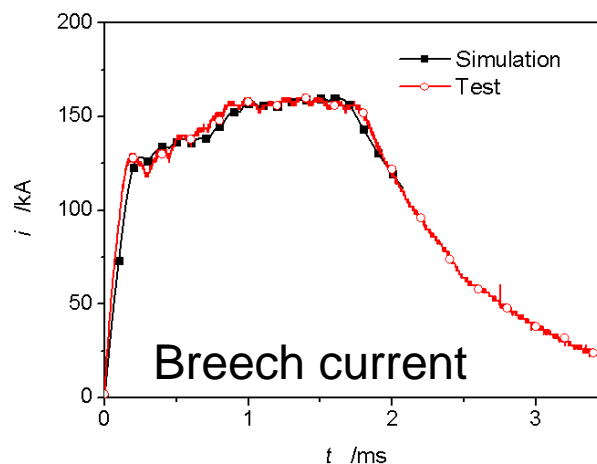
Velocity and acceleration



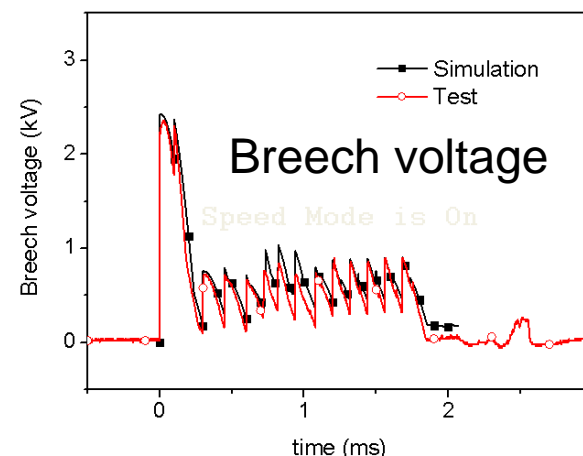
Transverse displacement



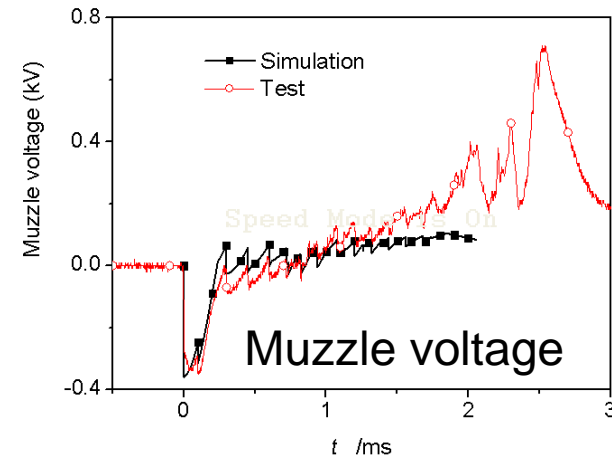
Transverse velocity



Breech current



Breech voltage



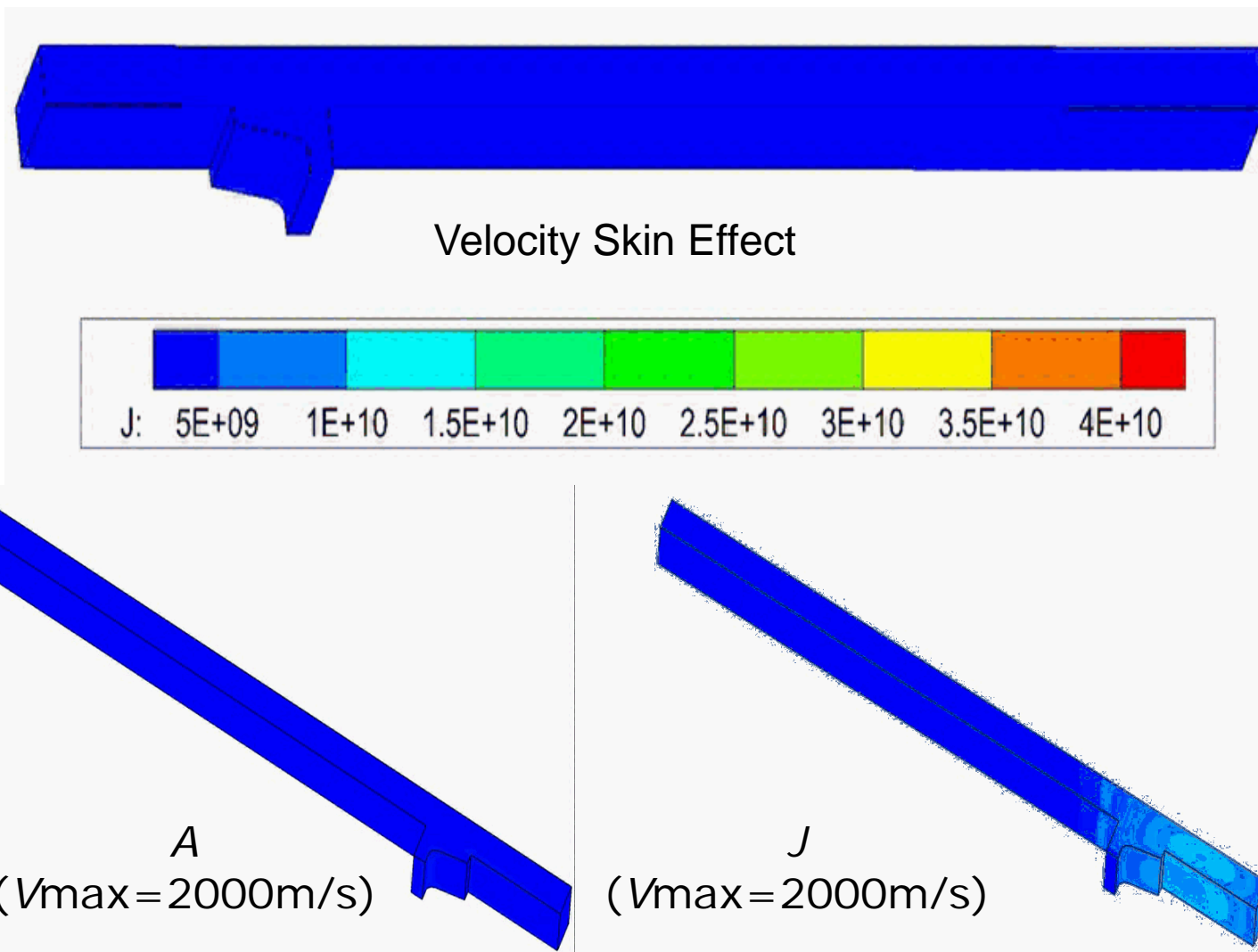
Muzzle voltage

We have developed a 3D multi-physical fields coupling model to simulate the EML process. Calculations include the electromagnetic, thermal and stress fields.

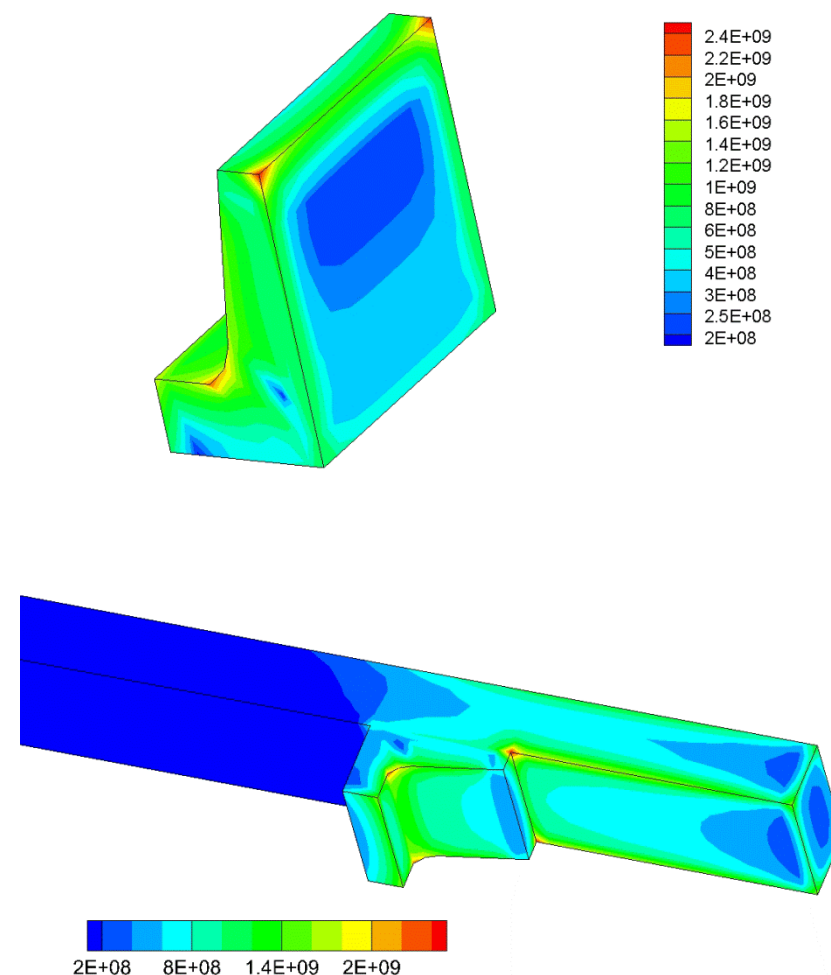


Interior Ballistics

3D Transient Multi-Physical Fields Simulation



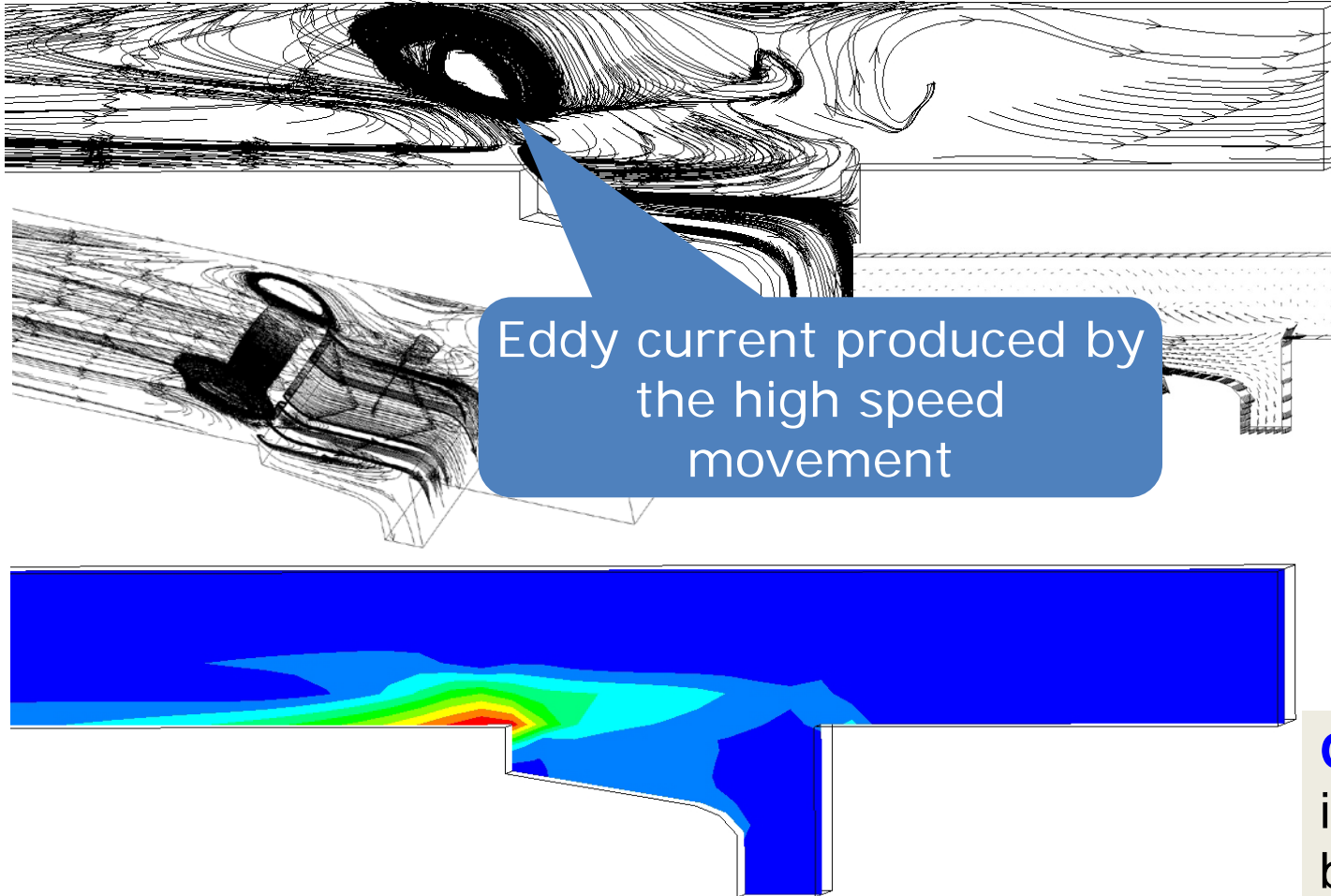
Electromagnetic Launch





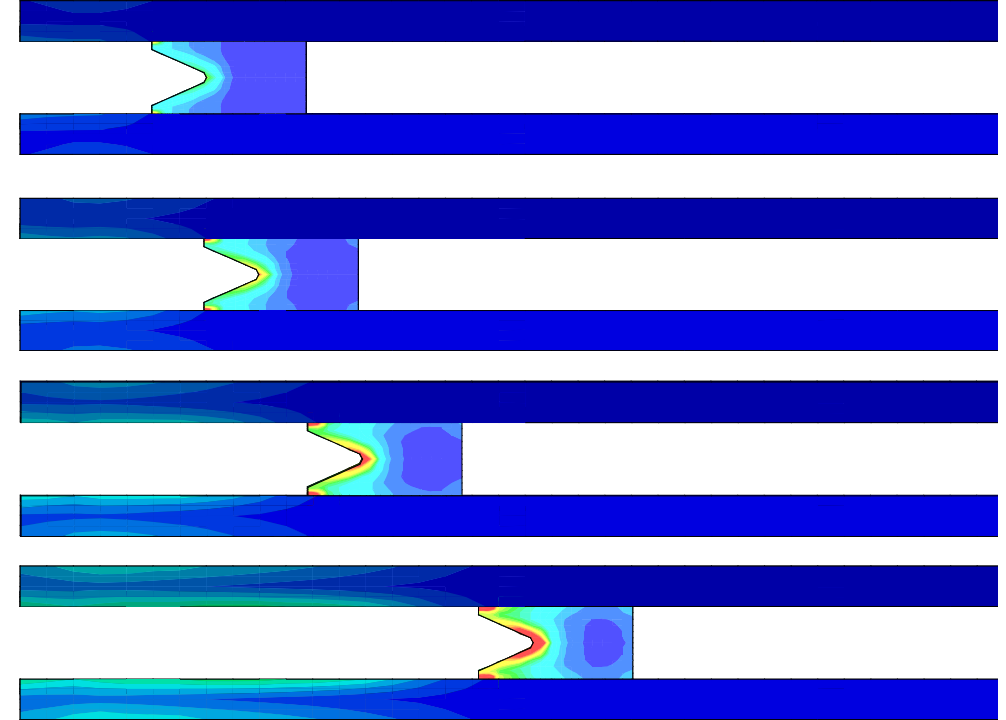
Interior Ballistics

3D Transient Multi-Physical Fields Simulation



Eddy current produced by the high speed movement

Electromagnetic Launch



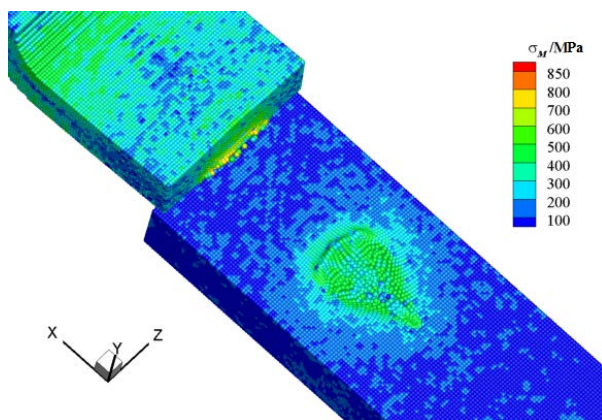
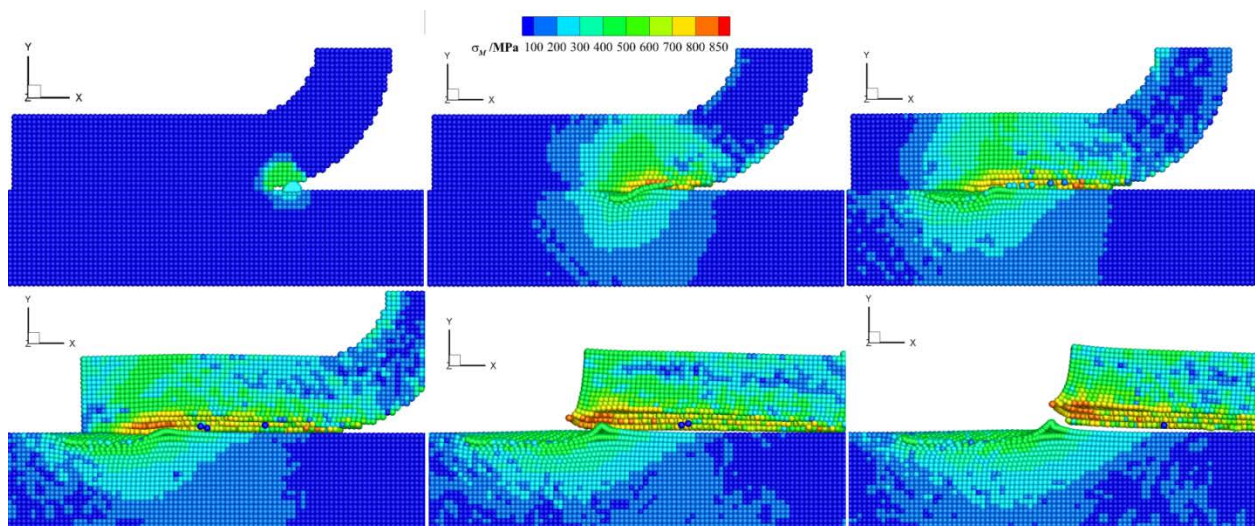
Ohmic heat: The rapid heat deposition will increase the temperature in the interface between rails and armature, which will lead to the happening of contact transition.



Interior Ballistics

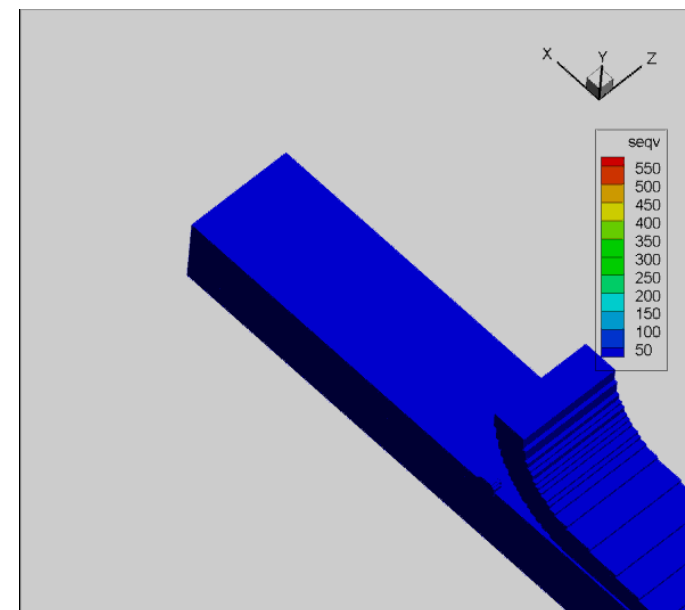
Impact Dynamics Simulation

Electromagnetic Launch



Gouging

High speed movement and swing of the armature may induce the gouging damage in the surface of rails.

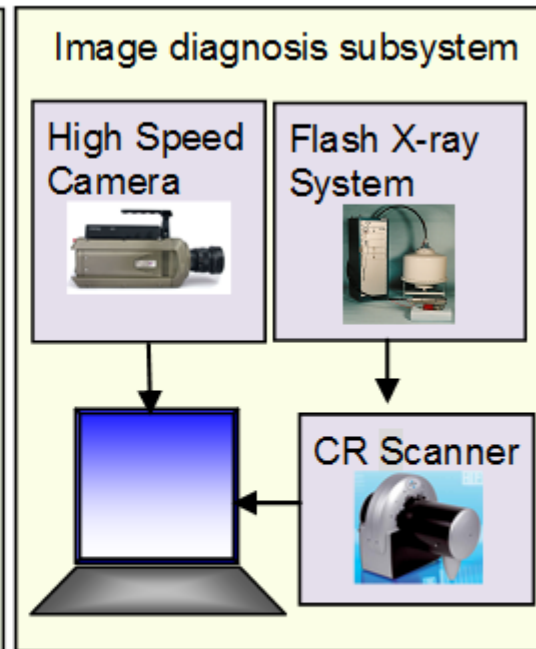
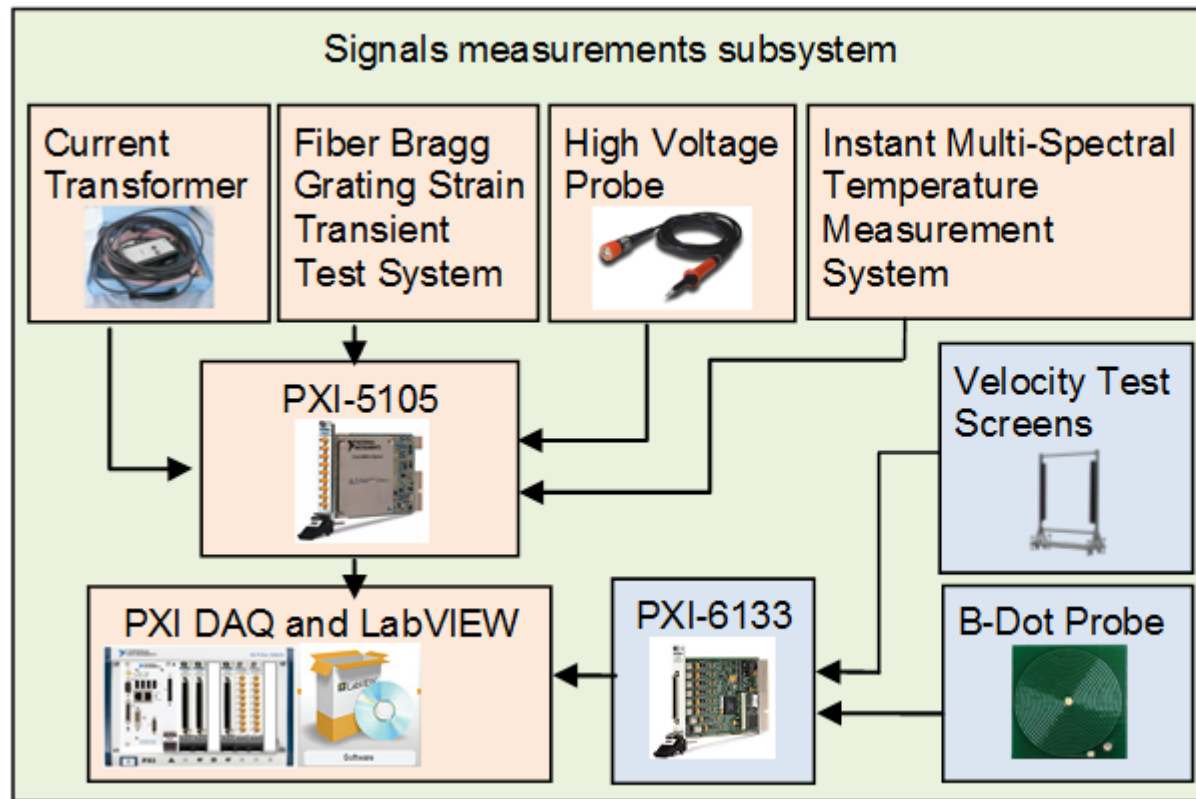




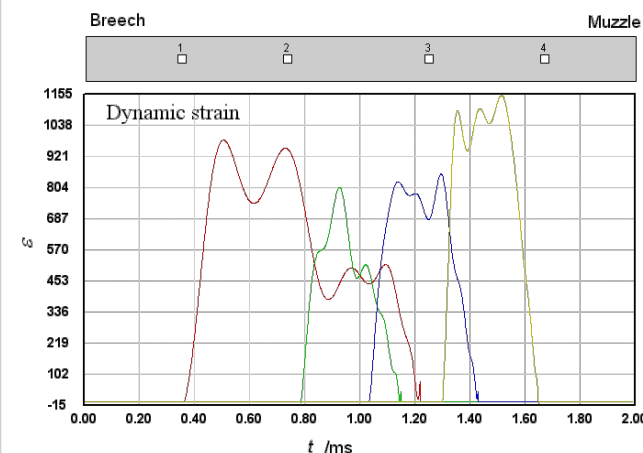
Interior Ballistics

Electromagnetic Launch

Multi-Physical Fields Measurement



Dynamic deformation and stress waves in railgun



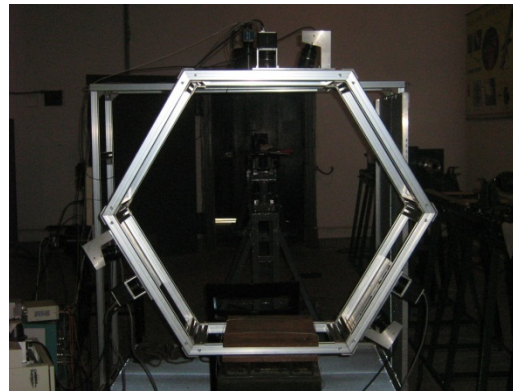
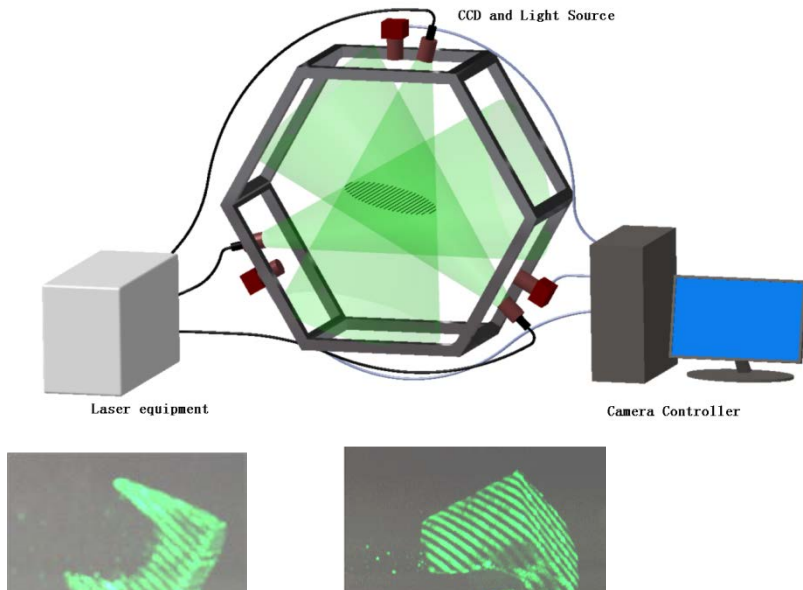
- ✓ Pulsed Current
- ✓ Pulsed Voltage
- ✓ Transient Plasma Temperature
- ✓ Transient Structure Strain
- ✓ Armature Surface Topography



Interior Ballistics

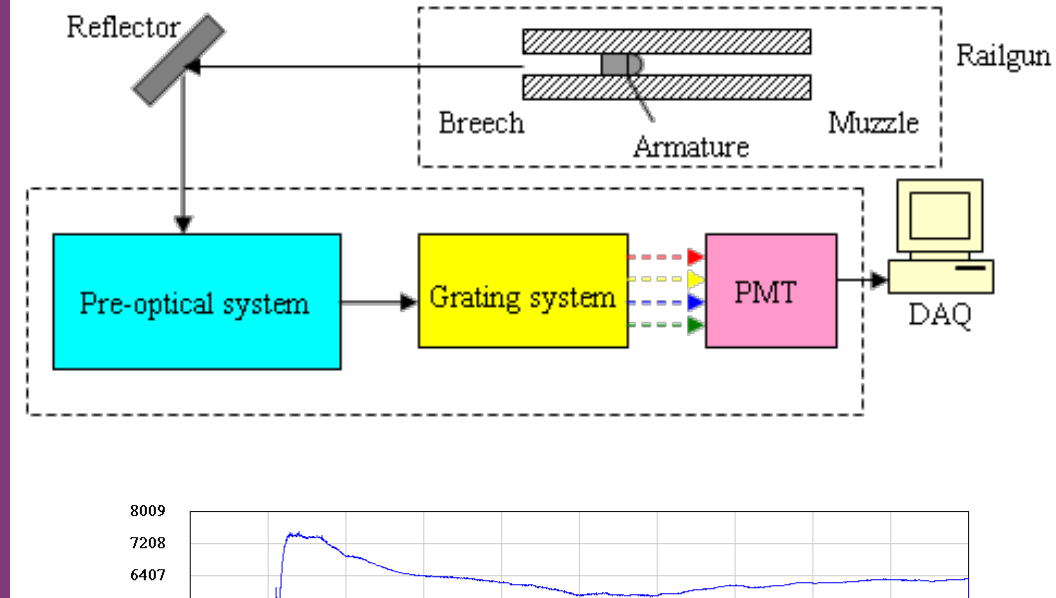
Multi-Physical Fields Measurement

3D Reconstruction



Electromagnetic Launch

Plasma Temperature



A pulse laser grating imaging system was developed to recover the armature shape when it is leaving the muzzle. Armature surface topography is reconstructed by the image processing algorithm.

The transient arc plasma thermal temperature in bore was measured using the Boltzmann plot method to characterize the contact transition.



CONTENT

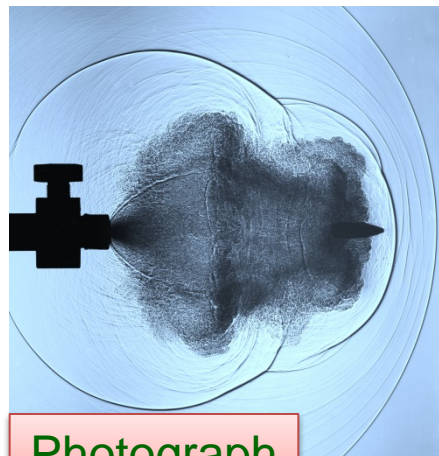


Muzzle Flow Field

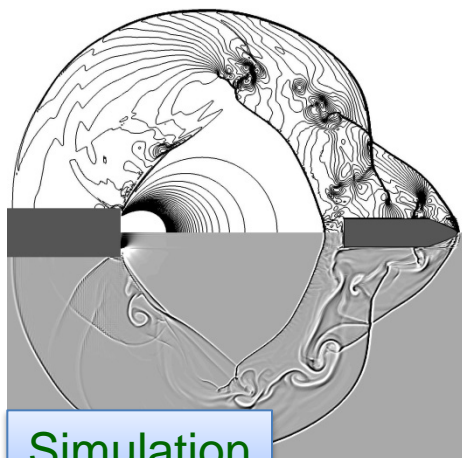


Intermediate Ballistics

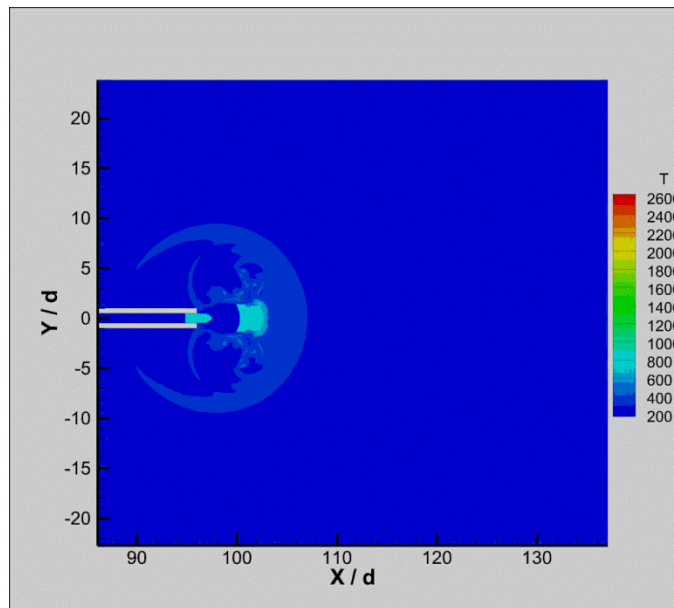
Muzzle Flow Fields of Barrel Weapon



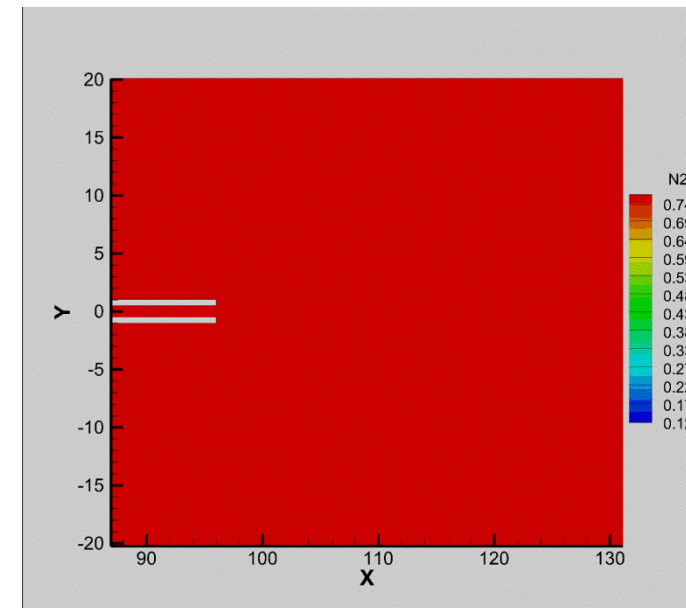
Photograph



Simulation



Temperature Distribution



N₂ Distribution

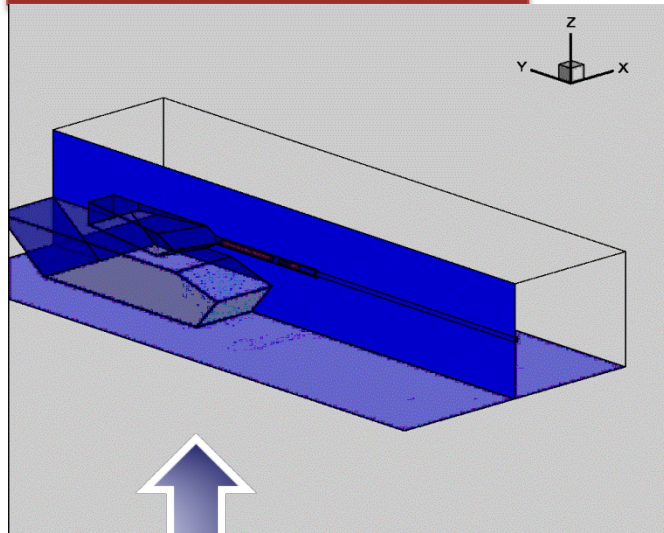
A numerical simulation program of muzzle flow has been developed by using large eddy simulation method and high accuracy hybrid numerical scheme.



Intermediate Ballistics

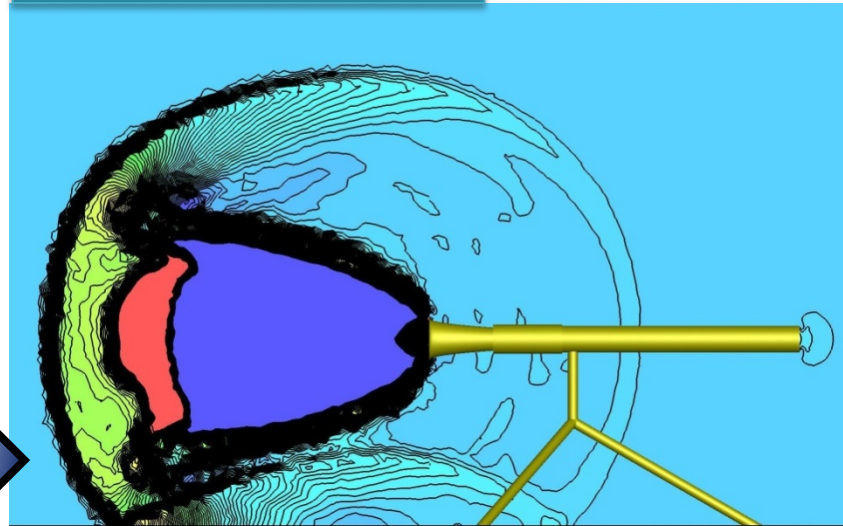
Muzzle Flow Fields of Barrel Weapon

Main Battle Tank



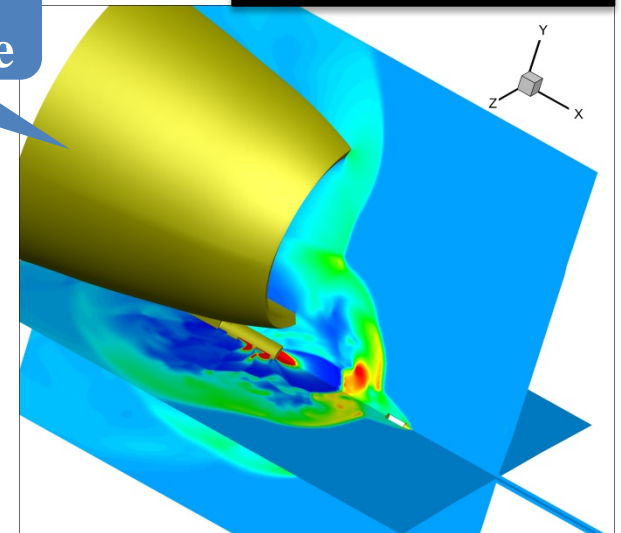
Considering the
ground influence

Recoilless Gun



Considering the
Air-inlet influence

Aircraft Gun





CONTENT



Exterior Ballistics



Pulse Detonation Engine



Range Extension Technique

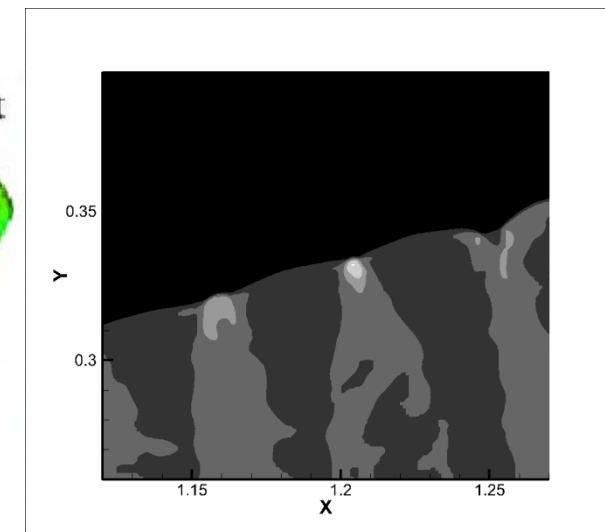
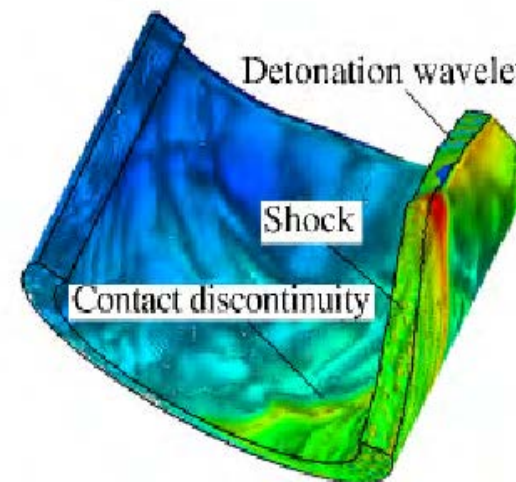
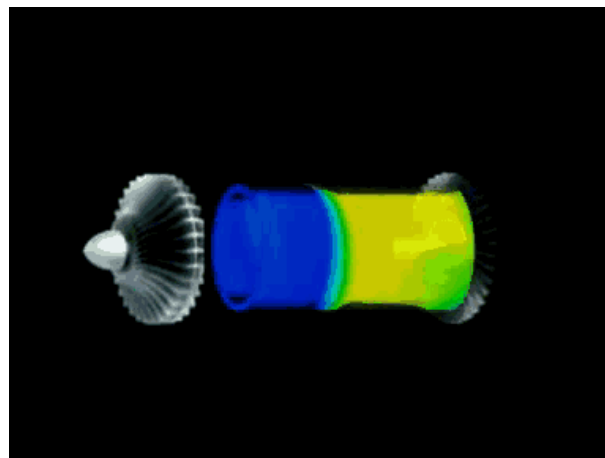
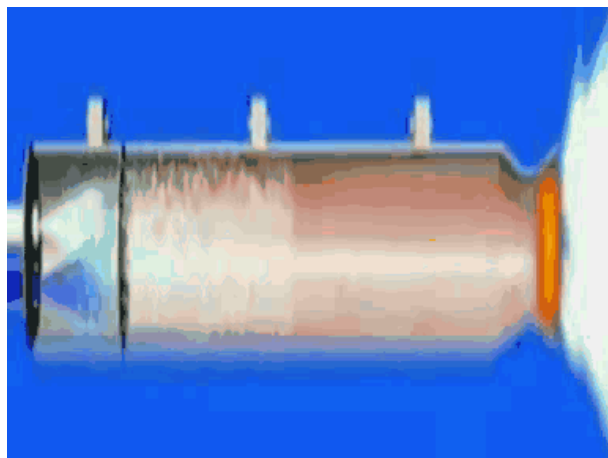


Flight Control Technology



Exterior Ballistics

Pulse Detonation Engine



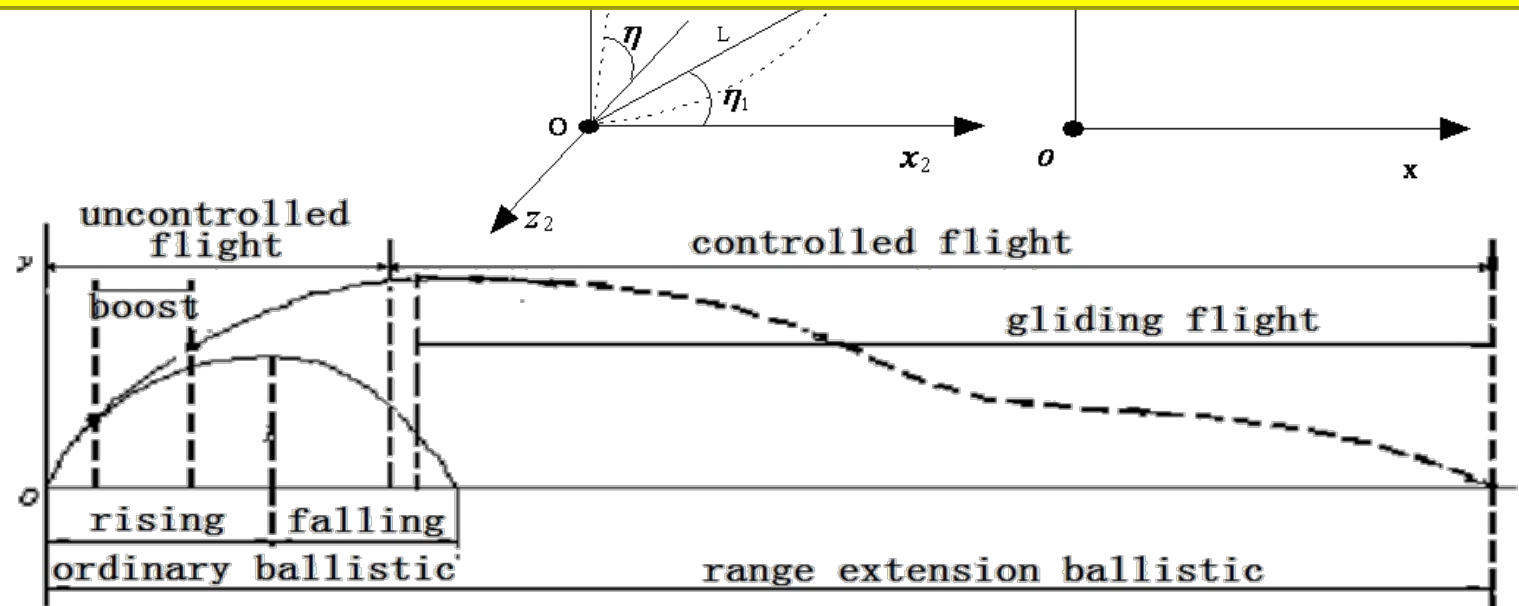
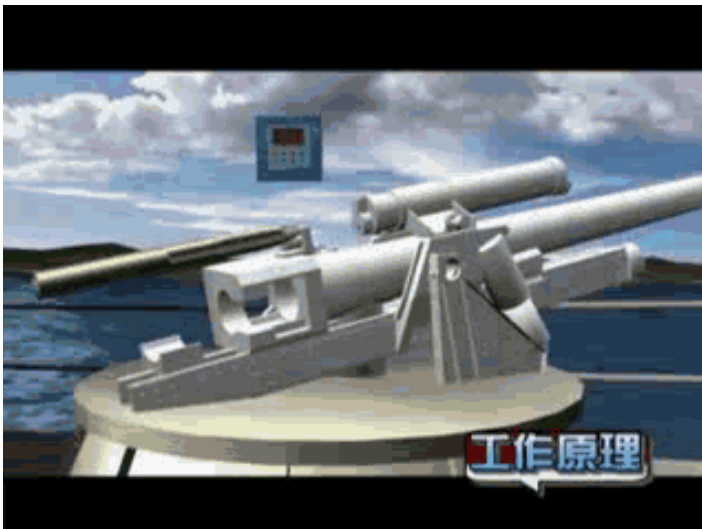
- In recent years, it was the first time that the liquid-fuel continuous rotating detonation engine was successfully initiated in China, which was a major breakthrough.
- The maximum peak value of rotating detonation wave pressure reached 3MPa, and the average value was 1.2MPa.
- Detonation wave velocity: 1022.2~1171.8 m/s.
- Detonation wave frequency: 2.1~2.4kHz.



Exterior Ballistics

Range Extension Technique

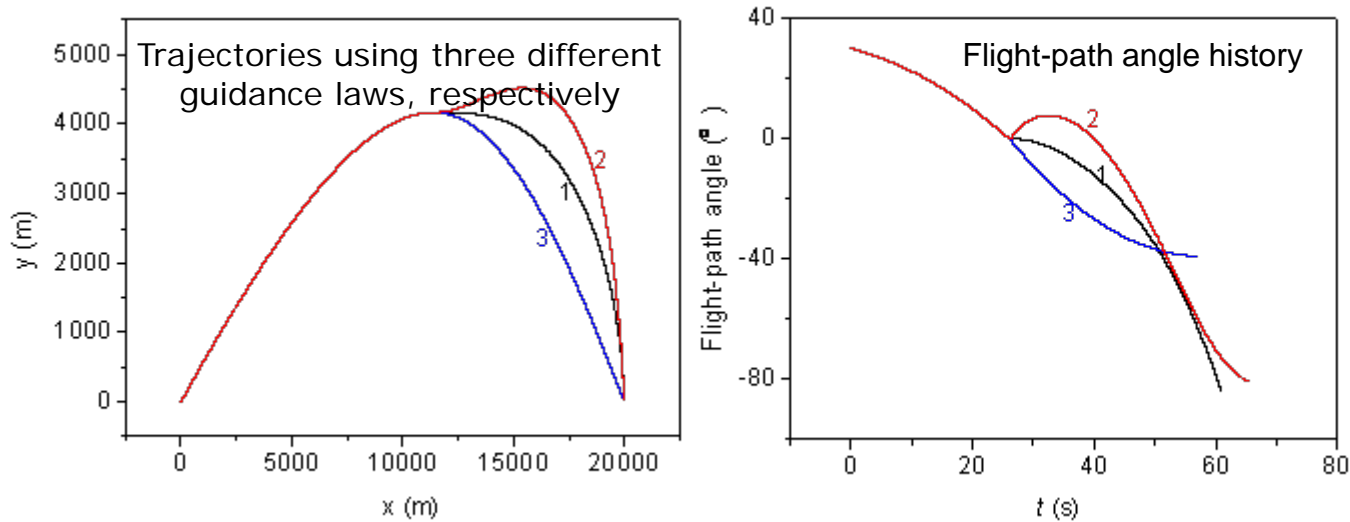
The optimal trajectory of gliding flight extended range projectile which has limited control variable was obtained by using Pontryagin maximum principle and conjugate gradient methods. The longitudinal channel control structure and control parameters are obtained. Due to the effect of atmosphere and other uncertain factors, robust control of pitching movement is so critical for the flight control.





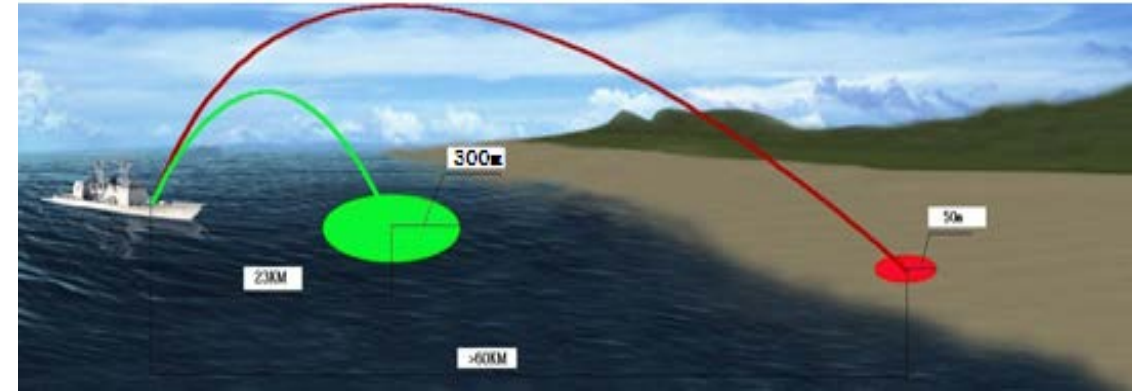
Exterior Ballistics

Flight Control Technology



Comparison of three guidance laws

Guidance law	Landing angle (degree)	Control energy consumption	Miss distance (meter)
Optimal guidance law	84.85	26.27	0.04
Suboptimal guidance law	80.74	34.42	0.07
Proportional navigation	38.94	12.47	0.28



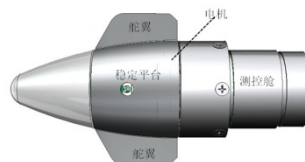
A design method of optimal guidance law is presented combining optimal control theory and piecewise function method. Compared to the proportional navigation law, the optimal guidance law is able to more than double the landing angle. Because of the steep terminal trajectory, the strike accuracy and damage effects are increased.



Exterior Ballistics

▶ Flight Control Technology

Mortar



Rocket



2-D Correction Flight

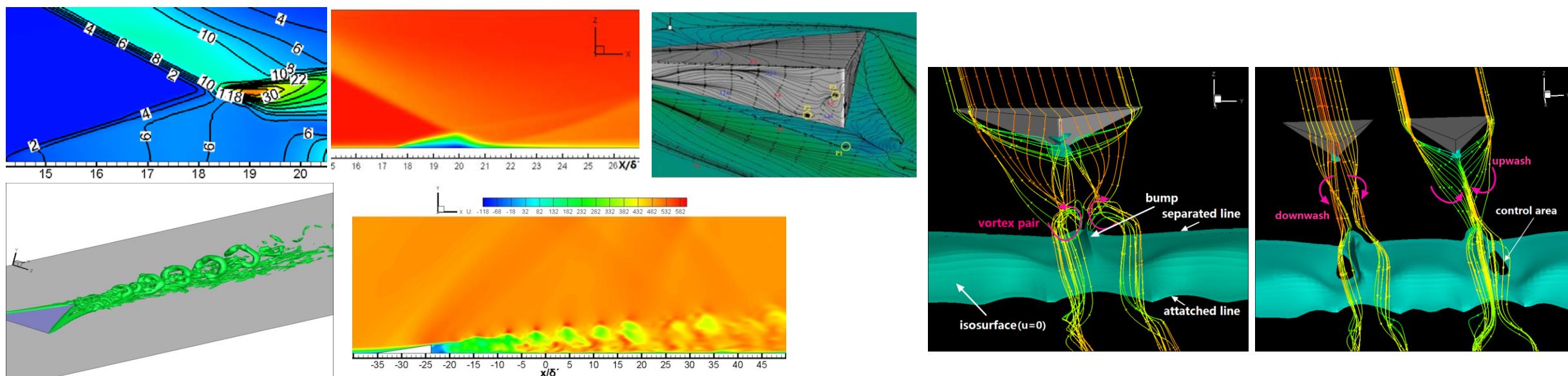




Exterior Ballistics

Flight Control Technology

Shock wave/boundary layer interactions and flow control based on MVG



Flow separation induced by shock wave/boundary layer interaction (SWBLI) is a ubiquitous phenomenon encountered in supersonic or hypersonic inlet. Based on large-eddy simulations, combined with high order numerical scheme, ghost fluid method and adaptive mesh refinement technique, the flow separation induced by the supersonic flow past an Micro-vertex generator (MVG) and the interaction of shock wave with boundary layer were investigated numerically. And their flow separation control mechanisms were obtained.



CONTENT



Terminal Ballistics



New Penetrating Technology



Penetration Effect of Various Targets

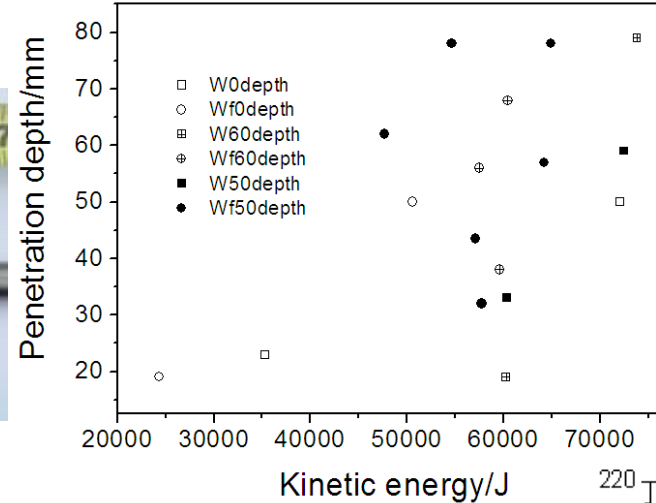
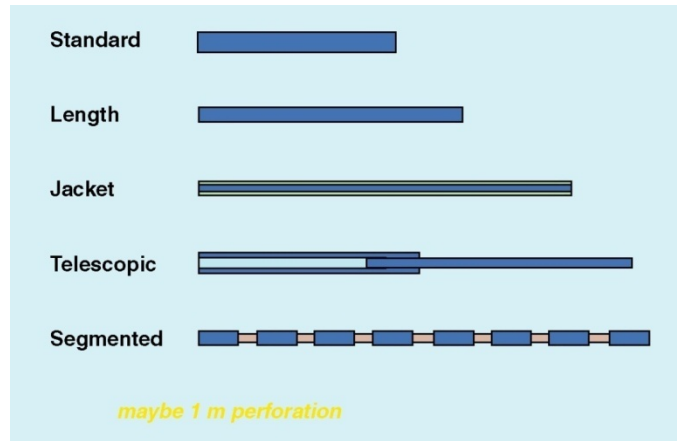


**Target Vulnerability and
Assessment of Damage Effects**

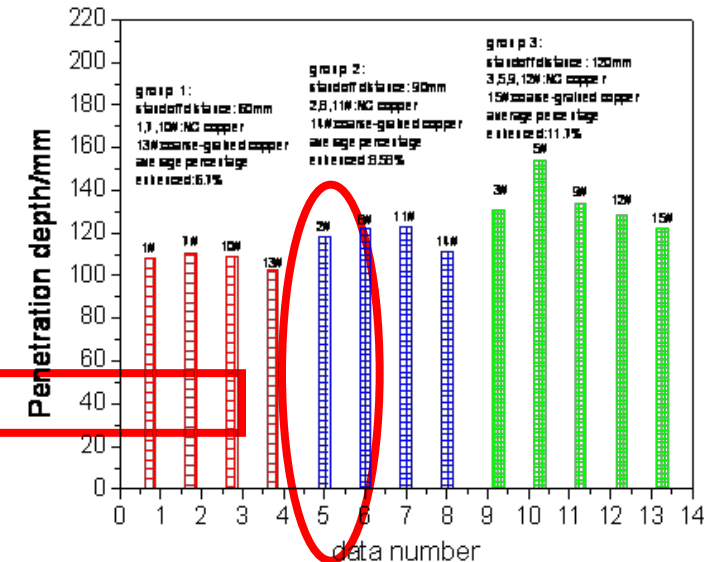
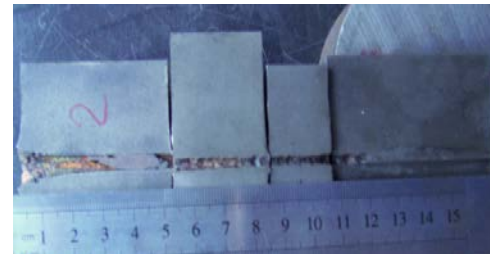
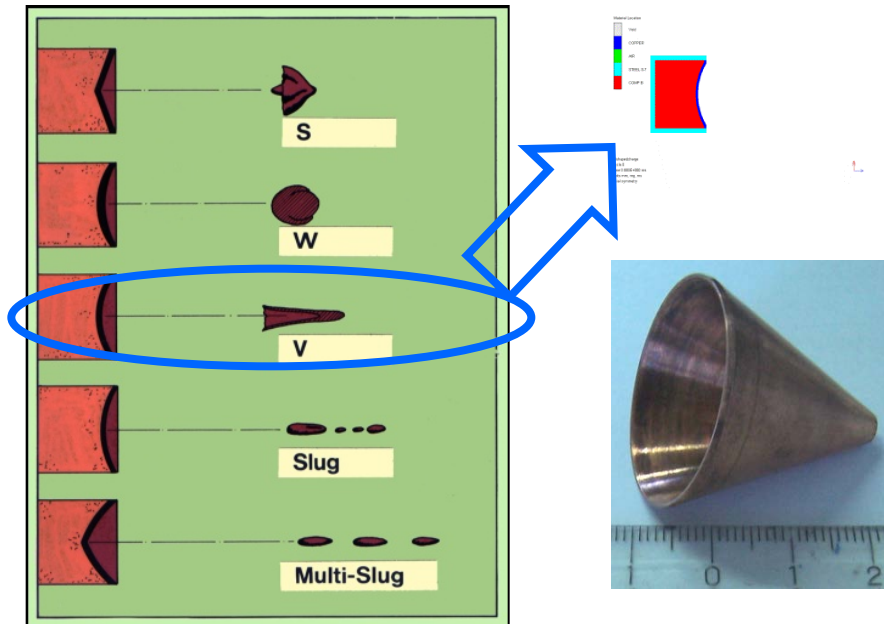


Simulation of Explosion and Penetration

We have conducted researches on the composite material formula, preparation technology of the micro/nano-crystalline penetrator core, and the self-sharpening effect of the micro/nano-crystalline penetrators, and shaped charge liner made of nano-crystalline and energetic materials.



- New materials
- New structures
- New principles





Terminal Ballistics

Penetration Effect of Various Targets



Experimental research were carried out for penetration effect of high velocity projectile above 2000 m/s.

(a) $v_0 = 2497 \text{ m/s}$ $\theta = 0^\circ$



Steel Front



Steel Back

(b) $v_0 = 2755 \text{ m/s}$ $\theta = 30^\circ$



Al Front



Al Back

(c) $v_0 = 2542 \text{ m/s}$ $\theta = 0^\circ$



Al Front



Al Back

(d) $v_0 = 2790 \text{ m/s}$ $\theta = 30^\circ$



Steel Front

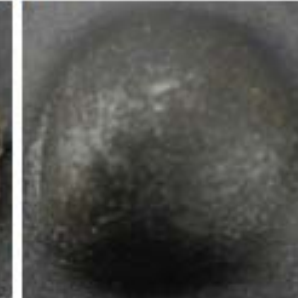


Steel Back

(e) $v_0 = 2572 \text{ m/s}$ $\theta = 30^\circ$



Steel Front

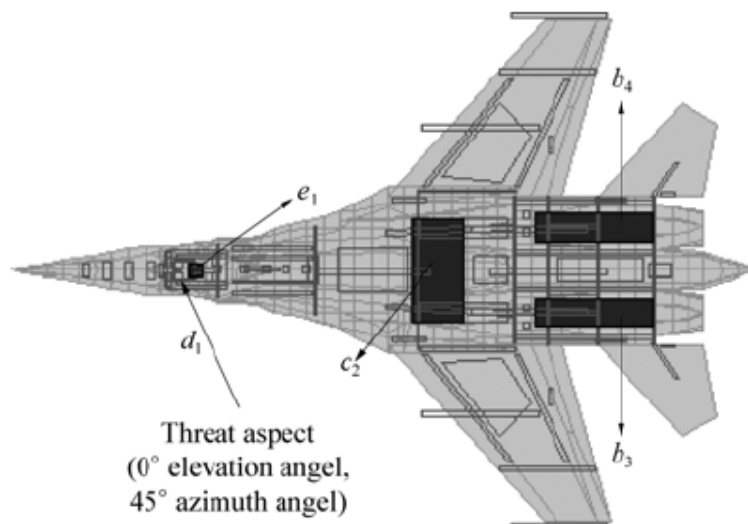


Steel Back

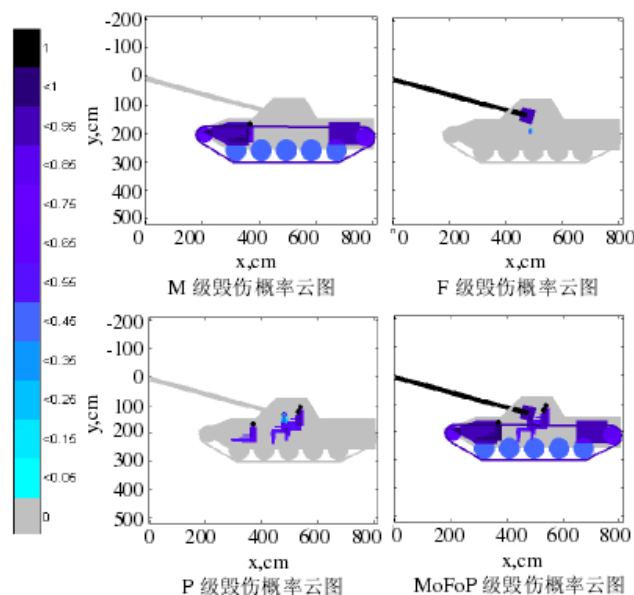


Terminal Ballistics

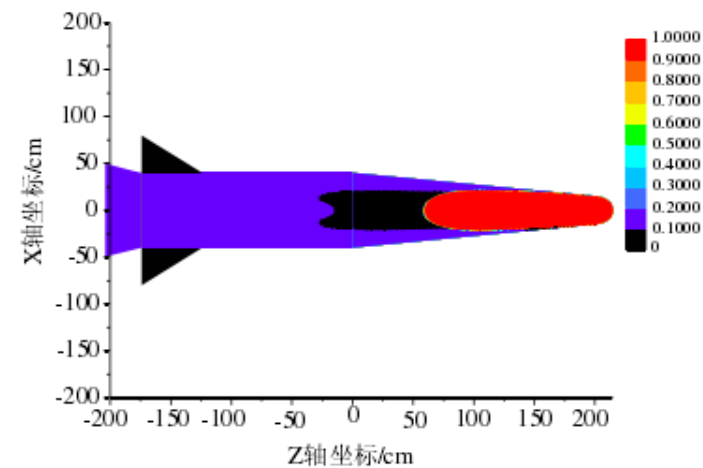
Target Vulnerability and Assessment of Damage Effects



Aircraft



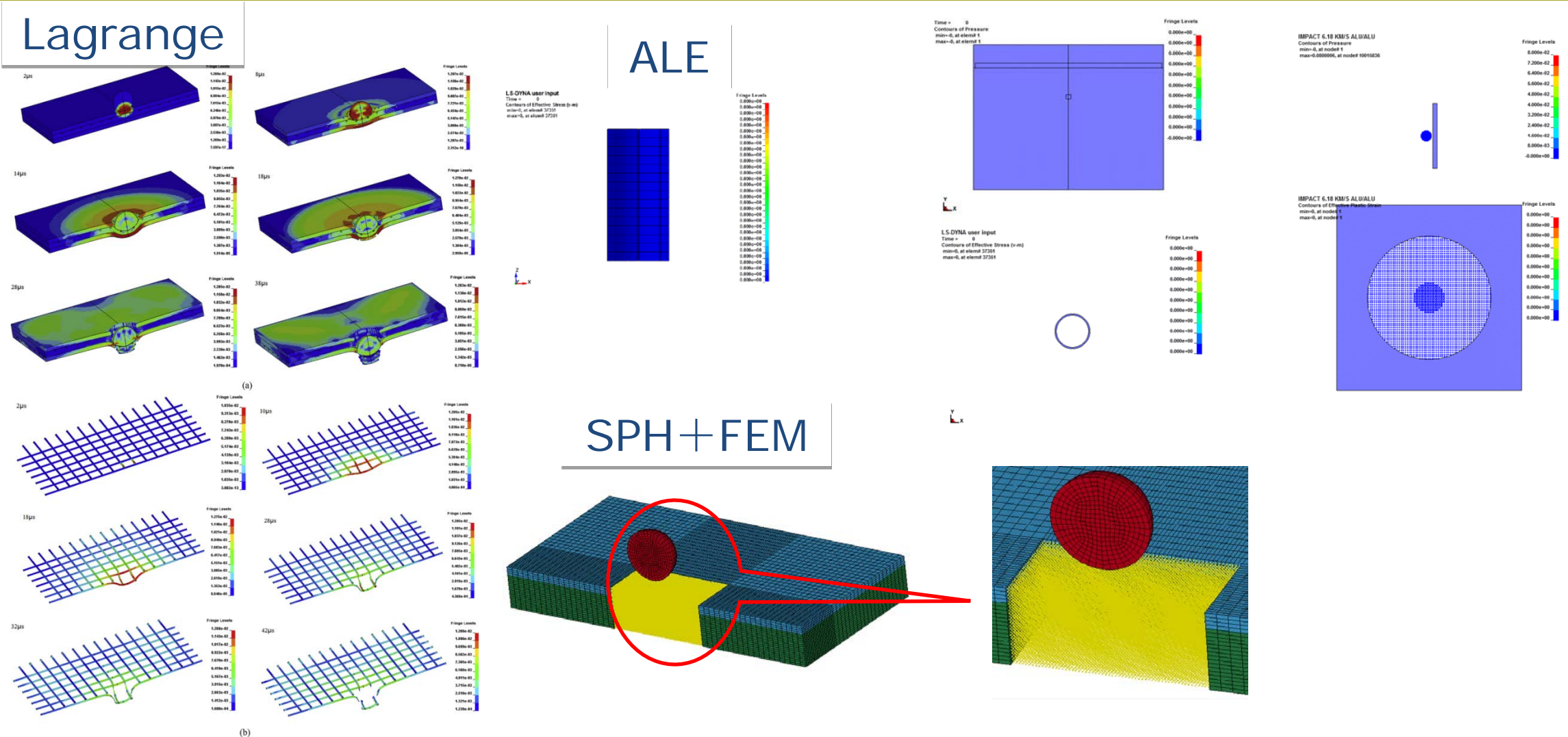
Tank



战术导弹弹头在动能拦截下发生 K 级毁伤的概率分布云图

Missile

A special software which is named EP3D was established. The finite element method (FEM), finite volume method (FVM), meshless method such as smooth particle hydrodynamic (SPH) were selected and applied in the EP3D. This software can play a great role for the development of high-efficient lethal technology.



Future Development



Interior Ballistics

Intermediate Ballistics

Exterior Ballistics

Terminal Ballistics

① Future Development of Interior Ballistics

ETC Launch

- Plasma enhanced control mechanism in the new propellant charge
- High efficiency coupling technology between the electric energy waveform and plasma
- Structure optimization design of plasma generator
- Plasma enhanced control of the high loading density propellants
- Develop the high precision measurement technology
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EM Launch

- High velocity guided projectile
- Extreme phenomena of multi-physical complex structural barrel
- Repeative stable launching Technology
- Muzzle arc management
-



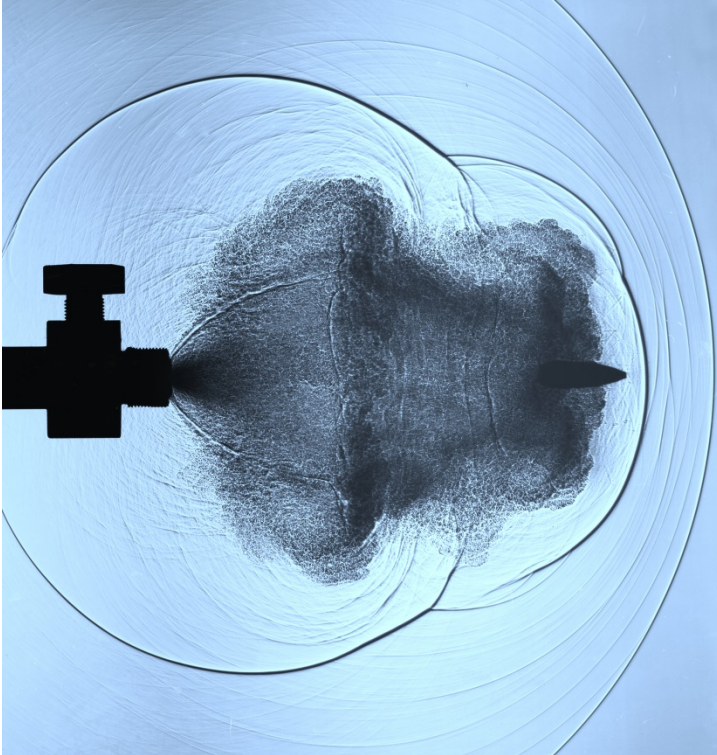
HFR Launch

- In order to cope with the threat of hypervelocity air-raid weapons, firing rate, range and caliber must be further increased in the future.
- Information-based ammunition also should be developed to improve the lethal capability.
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Future Development of Intermediate Ballistics



- Improvement of muzzle flow simulation program
- Turbulent combustion model of transient high-pressure flows with intensive blast
- Formation process of secondary blast
- Generation mechanism and suppression method of muzzle flash
- Devices for high precision measurement of muzzle flow temperature, muzzle pulse noise
- Experimental simulation system for high altitude environment
-



Future Development of Exterior Ballistics



Pulse Detonation Engine

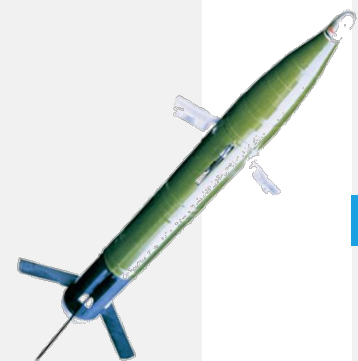
- High frequency
- High specific impulse
- Multi-barrel coordination
- Intellectualized flight control
- Increase of range and stability
-

Range Extension Technique

- Intelligence
- Networking
- High efficiency
-

Flight Control Technology

- Broad-airspace (over 30km height) and hypervelocity (over 5Ma) projectile of railgun, high-precision satellite or inertial guidance flight ballistics control technology used for autonomous precise guided cannonball, etc.



④ Future Development of Terminal Ballistics

Terminal effects of new defense structures and materials will be studied such as long rods and inhomogeneous complex long rod.

Multi-modes damage, smart mutilation, laser and microwave damage technique, etc. will be focused.

Terminal ballistics of hypervelocity (about 2500m/s) impact will be researched to improve penetration efficiency.

Develop new theoretical model and simulation method for the assessment of target vulnerability and damage.

Simulation will be focused on constitutive relations and physical parameters under high pressure of materials.

THANK YOU

10 May 2016 Edinburgh, Scotland